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WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK 2024

A global and regional forecast to 2050

FOREWORD

Last year, in the foreword to our 2023 *Energy Transition Outlook,* I wrote that the global energy transition had not truly started. Clean energy had not started replacing fossil energy in absolute terms. Now, one year later, we have reached that point. 2024 is the year that the global energy transition has begun; it is also the year that emissions are likely to peak.

Emissions peaking is, of course, good news, and a milestone for humanity. However, since emissions are cumulative, we must now focus on how quickly emissions decline. Worryingly, our forecast decline is very far from the trajectory required to meet the *Paris Agreement* targets. Our 'most likely' energy transition described in the pages that follow is one that leads to warming of 2.2°C by the close of this century.

If we want a faster transition, we must understand what is working and what is not.

Firstly, solar PV and batteries are booming, growing faster than we previously forecast. In 2023, new solar installations globally surged by 80% to reach 400 GW. One of the reasons solar is gaining ground so fast is because battery prices are plunging, making 24-hour solar+storage power more accessible. Battery prices fell 14% last year, and they will keep on falling. That means that EVs are poised to become cheaper too. The world is therefore still on track towards our long-standing prediction that 50% of new passenger vehicle sales worldwide will be electric by 2031.

> 2024 is the year that the global energy transition has begun; it is also the year that emissions are likely to peak.

Developments in solar and batteries are key reasons for emissions peaking. Owing to record EV sales in China, we are seeing petroleum demand there beginning to ebb away, while record solar installations are finally edging out coal in China's power sector. China's achievements in the production and export of clean technology are positive for the global transition, but are also facing a tariff backlash. Fully protecting all homegrown clean tech supply chains may come at too high a premium that risks slowing progress on decarbonization significantly. Policymakers must strike an admittedly very difficult balance between national security, economic goals, and *Paris Agreement* ambitions. Meanwhile, investing in clean tech recycling systems and digitalization/AI for efficient energy production, transmission, and use are no-regret choices.

Secondly, the transition is having difficulty with technologies for decarbonizing hard-to-electrify sectors, where market forces and policy are failing to address the challenges. Hydrogen and carbon capture and storage (CCS) are indispensable to a *Paris Agreement* aligned transition – or any transition that results in warming close to 2°C. Many of the first commercial hydrogen energy projects have experienced cost overruns or have been stopped amidst market uptake uncertainty.

We have revised our long-term forecast for hydrogen and its derivatives down by 20% (from 5% to 4% of final energy demand in 2050) since last year. Without a meaningful carbon price and/or direct market-stimulating support, hydrogen will struggle to scale and move down a cost-learning curve. The same holds true for CCS where our current forecast is that investment in CCS during our entire forecast period will be less than the amount invested in solar and wind in 2023 alone.

Policymakers should recall that the *Paris Agreement* involves a mission-oriented energy transition, and not one simply reliant on market forces. While the transition is now finally starting, its downwards trajectory is too slow because enabling policy is too weak.

In this Outlook, we quantify the many efficiencies gained from a doubling of electrification globally in the next 25 years. These efficiencies result in very large cumulative benefits that should give policymakers justification to tackle the difficult hard-to-electrify sectors while doubling down on renewable technologies, including much-needed short-term support for offshore wind.

I hope this year's Outlook inspires action, and as ever, we welcome your feedback.

Remi Eriksen

Remi Eriksen

Group President and CEO

DNV

Cover photo: Solar PV with co-located battery storage at the Gansu Dunhuang Solar Park, Gansu Province, China.

HIGHLIGHTS

① 2024 is likely the year of peak energy emissions, but the slow decline of post-peak emissions keeps key climate goals out of reach

② Slow developments in hard-to-electrify sectors contrast with rapid cost reduction and growth of PV and batteries

③ Highly competitive Chinese clean technology is speeding up the transition

④ National and economic security priorities dominate the international agenda and slow the transition

⑤ Market forces are necessary but insufficient; energy policy needs urgent alignment with climate goals

1. 2024 is likely the year of peak energy emissions, but the slow decline in post-peak emissions keeps key climate goals out of reach

– Solar PV installations are growing so rapidly that the need for coal power is reducing; global coal consumption in power stations is lower in 2024 than 2023. In the coming decade, the Indian Subcontinent is the only region with expected growth in power emissions.

– EV uptake is so high that peak gasoline in China is behind us and global peak oil is expected within a couple of years.

– The expected reduction in energy-related CO_2 emissions in 2025 (-0.4%) is marginal and not very certain. Unforeseen political or economic priorities may delay the peak by a year or two, but it is more likely than not that 2024 is the year of global peak energy-related CO_2 emissions.

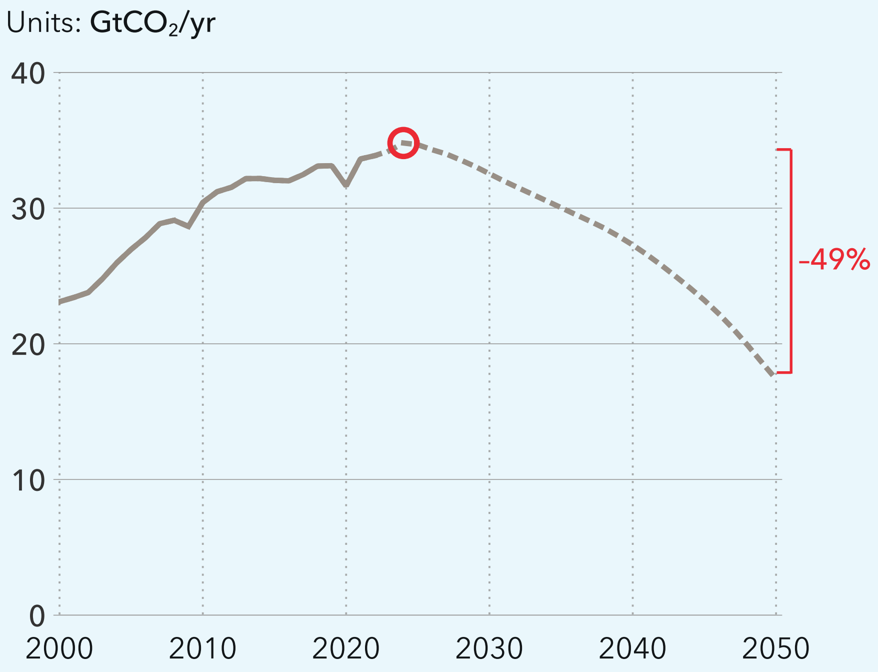
– Slow scaling of decarbonization solutions in hard-to-electrify sectors like heavy industry, maritime, and aviation is an ongoing challenge. Moreover we expect a strong increase in global aviation travel demand.

– Global energy-related CO_2 emissions reduce 5% by 2030, compared with 2023 levels. In 2050, CO_2 emissions are at 17 Gt CO_2. This is two decades later than the 2030 halving of CO_2 emissions outlined by the IPCC, and very far from net zero in 2050.

– Cumulative emissions drive a global temperature increase, and we are most likely heading towards 2.2°C of global warming in 2100.

HIGHLIGHT 1

World energy-related CO_2 emissions will peak in 2024



HIGHLIGHTS

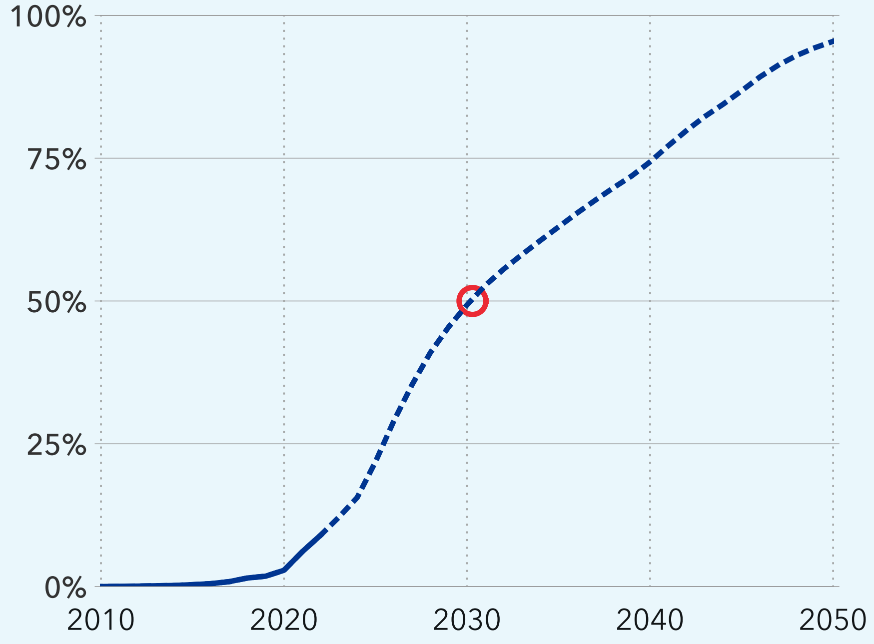
2. Slow developments in hard-to-electrify sectors contrast with rapid cost reduction and growth of PV and batteries

- Annual global solar installations increased 80% to 400 GW last year, will continue to increase in 2024, albeit with a lower growth rate.
- Solar+storage is growing fast, enabling 24-hour delivery of solar power.

HIGHLIGHT 2

Half of passenger vehicle sales are electric by 2031

Units: Percentages of sales



- EV sales increased 50% last year and are on track towards a 50% global passenger EV sales share in 2031. Already in 2025, we expect EVs to take a 25% share of new passenger vehicles sales globally.
- Costs of both PV and batteries continue to decline sharply, and the trend is expected to continue.
- There are slower developments in core decarbonization technologies needed for hard-to-electrify sectors: we have revised down both our short- and long-term forecasts for hydrogen. CCS is gaining some momentum, but overall volumes remain modest, with only 2% of global emissions captured by CCS in 2040 and 6% in 2050.
- Within electricity, offshore wind (down 18% in 2050 versus last year’s forecast) and small modular nuclear reactors are running behind earlier promises.
- Overall, renewables grow 2.2x from now to 2030, well behind the COP28 goal of tripling to 2030.
- Near-term energy efficiency improvements are also relatively slow. Global energy intensity improves 2%/yr to 2030, only half of the 4%/yr target from COP28.

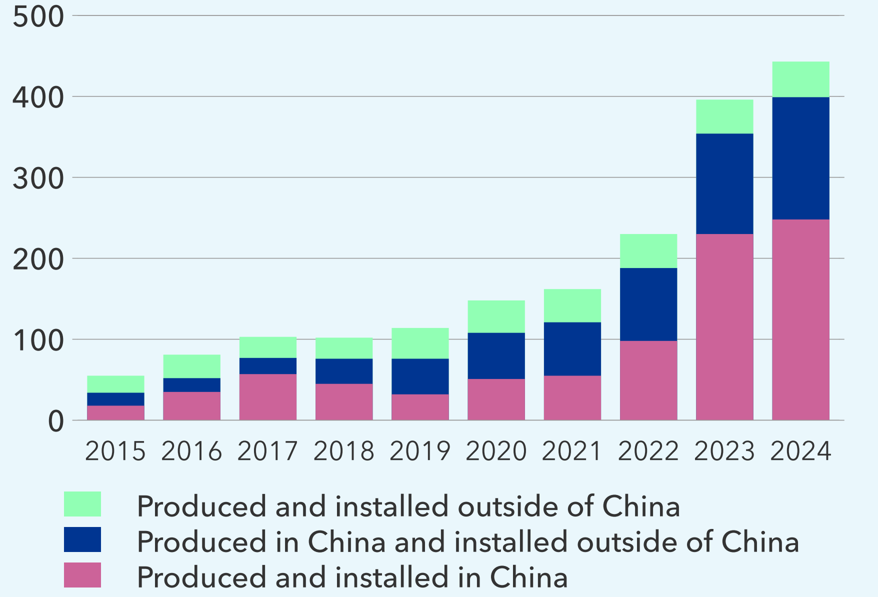
3. Highly competitive Chinese clean technology is speeding up the transition

- China has pursued strategic industrial policies on 'new energy' technologies for decades and now dominates the manufacture of almost all of those technologies. The Chinese domestic market provides a scale advantage: in 2023 China accounted for 58% of global solar installations and 63% of new EV purchases.

HIGHLIGHT 3

China dominates global solar PV installations

Units: GW installed annually



Note: Capacities in AC

Historical data source: GlobalData (2024), IRENA (2024), IEA (2024), Ember (2024)

- China’s exports of low-cost clean technologies and overseas direct investments enables the transition abroad: with solar PV and batteries dominating export and wind turbines and electrolysers growing.
- National, economic, and energy security considerations are leading to tariffs and other protectionist policies for home-grown supply chains and manufacturing in North America and Europe in particular.
- Diversifying from China too rapidly risks a sharp increase in supply chain and production costs, a duplication of innovation effort, and a slower transition.
- Alternative supply chains will take root, with sectors like battery storage which are of strategic security importance being prioritized, following substantial government investment in research and innovation, sourcing, and production support. In our model we reduce the temporary cost disadvantage of alternative supply chains over time.

HIGHLIGHTS

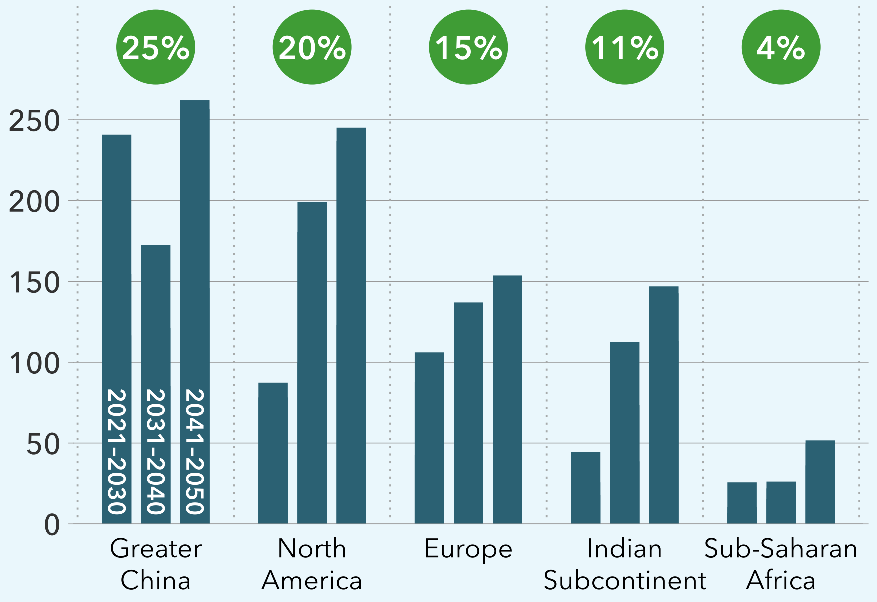
4. National economic and security priorities are headwinds for the transition

- Regional conflicts, geopolitical tensions, and growing security concerns are heightening military focus and spending.
- Budgetary pressure is diverting government support away from both domestic transitions and development aid financing the transition in the Global South. Sub-Saharan Africa's share in global renewables investment from now until 2050 is expected to be only 4%.
- High borrowing costs, albeit slightly easing, continue to squeeze public budgets and prolong a cost-of-living crisis in many individual households.
- Extreme weather events are draining budgets and yet not cementing climate action.
- A lack of effective action across all tiers of government addressing permitting delays/ NIMBYism and other regulatory delays making renewable projects less profitable in several regions.
- Rising biodiversity concerns challenge renewable/ grid developments. Aligning with the Global Biodiversity Framework is important; however, regulation does not (yet) reflect that climate change will surpass land use changes as the number one cause of biodiversity loss before 2050.
- In some instances, energy security priorities are speeding up the transition, like the accelerated renewable buildout in Europe, while elsewhere energy security favours continued expansion in fossil fuels.

HIGHLIGHT 4

Investment in renewable power will be concentrated in a handful of regions

Units: USD billion/yr



Bubbles show regional share of global investment over the 2021-2050 period

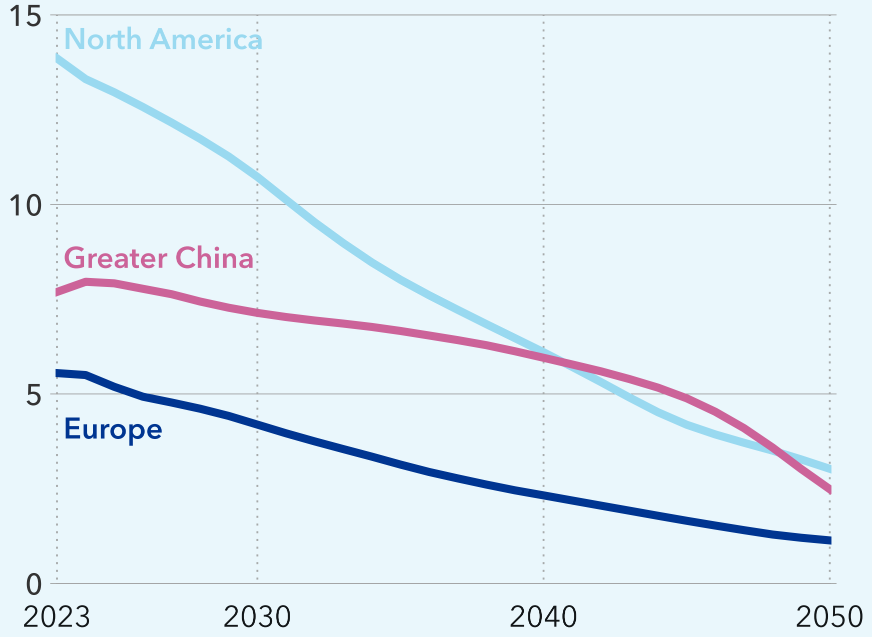
5. Market forces are necessary but insufficient; energy policy needs urgent alignment with climate goals

- Market forces alone cannot achieve the *Paris Agreement*'s goal of keeping the temperature rise well below 2°C. While markets are often effective in promoting renewable electricity and EV uptake, they fall short in addressing costly and complex technological measures in other sectors.
- Market forces are distorted because externalities are not priced correctly. This inhibits fossil fuel substitution, carbon capture and removal, and energy efficiency investments. Fossil subsidies in the forms of 'contracts' to citizens and producer support are widespread and block decarbonization.
- A cost on carbon is needed to achieve sufficiently rapid emissions reductions. While the US follows an incentive-based approach to promote renewables and clean energy uptake, the lack of disincentives results in persistently high emissions. China's carbon pricing is evolving in scope but start late and remains at a low level compared with Europe.
- The virtual disappearance of emissions in Europe by 2050 (as shown below) is due to the comprehensiveness of its decarbonization policies – combining incentives for renewables uptake with disincentives, including a high carbon price, for continued unabated fossil use.

HIGHLIGHT 5

CO_2 energy-related emissions per capita will decrease, but at different paces

Units: tCO_2/yr



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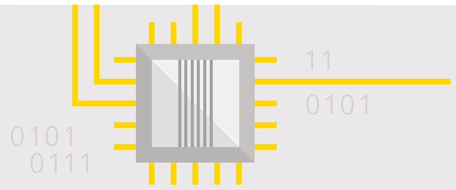
INTRODUCTION

About this Outlook: This annual *Energy Transition Outlook* (ETO), now in its 8th edition, presents the results from our independent model of the world's energy system. It covers the period through to 2050 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

Our forecast data may be accessed at eto.dnv.com/data

More details on our methodology and model can be found on page 243. The changes we forecast hold significant risks and opportunities across many industries. Some of these are detailed in our supplementary reports for 2024:

- *Maritime forecast to 2050*
- *New Power Systems to 2050*

Over the last year, we extended our model to enable the production of forecasts at country level. In 2024 we have issued ETO reports on the UK and China, with reports on Norway, Spain, and Germany forthcoming. All ETO reports are freely available on dnv.com/eto.

Our approach

DNV presents a single 'best estimate' forecast of the energy future, with sensitivities considered in relation to our main conclusions. Other guiding principles informing our approach are listed graphically alongside.

Significant updates to our model this year

All updates to our model over the last 12 months are listed on page 244 or this report. These updates include:

- Incorporation of the new policy landscape, particularly the comprehensive US IRA package, renewable power support, hydrogen support, and CCS support.
- Updated formulation for nuclear, specifically the distinction between small modular reactors and large scale nuclear, and different technologies.
- Representation of biodiversity considerations in power investment costs.
- Representation of societal feedback on power project pipeline, success rate, and construction times.
- Adjustments to power sector investment costs, considering regional preferences for or against specific technologies due to energy security considerations.
- Representation of the effect of reshoring on cost trajectories.

Independent view

DNV was founded 160 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 is related 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 100 professionals in DNV. In addition, we are very grateful for the assistance provided by external experts and other companies researching the energy transition. All contributors are listed on the last page of this report.

GEOPOLITICS DRIVING ENERGY SECURITY AND INDEPENDENCE

The present geopolitical environment, marked by growing tensions between China and the West, the Ukraine war, Middle Eastern conflicts, and persistent North-South inequalities, is generating uncertainty in energy markets. Nations now increasingly value energy security over both affordability and sustainability. Our forecast considers critical factors such as the added costs for energy security and the expense of bringing manufacturing back home. We explore the tension between the push for energy independence which often favours renewables, and the push for homegrown supply chains for clean technology that threatens to raise costs and obstruct global collaboration. Analysing the impact of geopolitics on a global industry involves navigating intricate and evolving dynamics, but we assess the current situation as somewhat unfavourable for the energy transition.

Global trade as a proportion of GDP has increased nearly fourfold since the end of World War II, invigorated by technological advancements and the relative stability of the post-war era. Three decades of trade liberalization following the Cold War and the integration of China in the global economy has propelled global trade, helped by cheap global shipping transport. Industries have established international value chains for efficiencies through specialization and comparative cost advantages. These changes have brought benefits for consumers world-wide and significantly improved living standards in middle-income countries and regions like China, South East Asia, and Latin America.

Geopolitical decoupling

Since the financial crisis, the world has entered a period of slower expansion of cross-border cooperation and trade. Over the last decade we have also witnessed growing geopolitical rivalry, in particular between the US and China. The COVID-19 pandemic exposed the vulnerabilities and dependencies of international value chains. Concerns over fragile supply chains intensified following Russia's invasion of Ukraine in February 2022. The war immediately jeopardized food security, both directly in terms of Ukraine grain exports and by disrupting fertilizer supplies. However, the most significant impact has been on global energy supply chains. With Russia supplying approximately 45% of Europe’s natural gas in 2021, the conflict sparked serious energy security concerns across the continent. As Europe scrambled to find alternative gas sources, energy prices surged to record levels, causing global market imbalances and disruptions. This crisis accelerated Europe’s push towards energy diversification and a green energy transition, emphasizing renewable energy and energy efficiency measures.

These events have further prompted nations and companies to rethink their supply chains and address vulnerabilities. The initial mindset of ‘better, cheaper, faster’ approaches, coupled with over-reliance on a few manufacturing hubs and a lack of visibility into supply-chain dynamics, has given way to a growing awareness of the need for resilience. The vulnerabilities exposed have led to a push for diversification. A key driver behind this shift is national security, as many countries no longer see sourcing from the global market as sufficiently secure to protect their national interests. Governments are increasingly using mandates and bans and offering policy incentives to relocate or build (green) value chains within their borders, particularly in strategic sectors. For instance, in microchip production, governments are enacting legislation to secure national supply chains by investing in domestic research, development, and production. This shift reflects a broader trend of prioritizing national security over global market reliance, as nations seek to safeguard critical industries – and the energy industry among them – against external disruptions.

The energy supply shock of 2022 has altered international relations, marking the beginning of an era where energy security takes precedence in the energy trilemma. Concerns about energy security vary across regions: energy-importing regions will prioritize resources that are locally available or can be sourced from reliable partners, while exporting countries will need to prove themselves as dependable, long-term suppliers. We also see

import nations benefit from the crisis buying energy commodities at rebated prices when the commodities cannot be sold on an open world market.

The effect on the energy transition
Energy security generally pulls in favour of renewable energy production as the obvious, low cost, domestically available resource. Nuclear energy is similarly favoured. Energy security, however, can also slow the transition if countries turn to available fossil resources to address energy shortfalls, rather than investing in renewable energy production. The intensified focus on energy security also includes security of green value chains. Many regions are reviewing their dependence on other regions providing the raw materials; components and equipment for renewable energy production (wind turbines, batteries) and electrification on the demand side (EVs, electrolysers). Enhancing security of supply is achievable through increasing domestic energy and resource production, diversification of energy sources in the supply mix, or diversification geographically by using a variety of suppliers and transportation routes.

Some of the trends include:

Energy security as a part of national security – ensuring continuous access to reliable power has become a vital priority for modern societies and energy security is therefore recognized as a key element of national security. As energy markets remain volatile and global cooperation slows, countries are prioritizing local energy resources to protect their national interests, recognizing that 24/7 access to power is essential for the smooth functioning of modern society, where disruptions could have serious economic and strategic consequences.

A future with volatile energy prices – the surge in energy prices resulting from Russia's invasion of Ukraine have heightened concerns about the future stability of global energy markets. In regions that have not imposed sanctions on Russian oil exports, short-term benefits from cheaper imports have emerged, but they also raise concerns about long-term dependencies on unstable supply chains. Low- and middle-income countries were made to regret their dependence on imported natural gas, as high-income countries outbid traditional buyers forcing them to switch to more readily available local resources, such as coal, to secure energy supplies. This shift underscores the growing complexity and unpredictability of global energy dynamics.

Investments in strategic energy infrastructure – including energy storage and smart grid technology, are advancing to provide secure access to energy. This leads to increased deployment of renewable and also nuclear energy. However, investments in fossil infrastructure, like regasification terminals or pipelines could also fall under the 'national security' rubric, and carry the risk of locking countries into a carbon-intensive energy system for years to come.

Remaking of global supply chains – is taking place in a number of key commodities and is affecting the cost and routing of key energy infrastructure. The disruption in global production and delivery of key intermediate goods, such as steel and computer chips, has led to significant changes in trade routes, contributing to increased supply chain costs. As companies seek to mitigate these disruptions, they are considering strategies like re-shoring or friend-shoring to bring production closer to home or to trusted partner nations. These shifts, combined with import tariffs, are straining global manufacturing supply chains. The renewable energy sector, with its typically tighter margins compared with oil and gas, has been hit particularly hard. This has resulted in rising project cost estimates, delays, and in some cases cancellations.

Security of green value chains – the intensified focus on energy security has expanded to encompass the security of supply of critical raw materials and key components and equipment of green value chains (such as wind turbines, batteries, electrolysers and EVs) as a policy priority. Many countries are reviewing their strategy and dependence on other countries providing the raw materials necessary for securing their energy supply or transition, and are hence increasing incentives for local sourcing and production. The effect will further augment existing imbalances and could affect costs in the short to medium term.

Nuclear as a possible alternative – the focus on energy security has made nuclear energy a seemingly more attractive option for some countries. We see concrete life-extension programmes in several countries, and also a limited number of new initiatives in both existing and novel nuclear countries, Poland being one example in Europe. Whether nuclear uptake will accelerate will depend on how nuclear manages to solve some of the same challenges it has faced before, such as cost overruns, safety concerns, waste handling, public opinion, and the proliferation risks associated with a potential higher uptake. General energy security concerns are, however, likely to partly accept the higher costs of nuclear, which leads to a slightly higher uptake. On the downside, it is more controversial to accept nuclear technologies from 'non-coalition' countries, like in Finland where a project based on Rosatom design was immediately cancelled.

Societal pushback – inflation and the cost-of living crisis have stoked social unrest which could delay the energy transition as the focus shifts to short-term priorities. Conversely, it is possible that public sentiment could favour energy independence through renewables and nuclear and the acceptance of higher energy prices as strategic means to secure energy independence.

> Many countries are reviewing their strategy and dependence on other countries providing the raw materials necessary for securing their energy supply or transition, and are hence increasing incentives for local sourcing and production.

How we incorporate energy security and geopolitical trends into our forecast

The geopolitical changes and energy security described above have a direct impact on the energy transition and we are therefore factoring both energy security considerations, reshoring of manufacturing, and a modest restructuring of the global economy into our forecast of the most likely energy future.

Energy security considerations in the power sector
In a more polarized world, nations and regions are increasingly supporting domestic energy production to curb their dependence on uncertain energy imports and to hedge against the potential weaponization of energy. In some cases, energy resources which are predominantly imported are being penalized or deprioritized, even if short-term economics favour those sources. The prioritization of energy resources depends, inter alia, on the availability of different energy resources within a country's borders and on technological know-how and availability of a qualified workforce.

This behaviour is most pronounced in the power sector, and in our power model we are reflecting energy security considerations. These considerations can favour both low-carbon and fossil-based energy resources depending on the domestic resources available. For example, regions such as Europe will prioritize nuclear and renewables, while the Indian Subcontinent will prioritize domestically available coal. In the model, the regional policy support level reflects the actual and likely future support to the various power sources.

Reshoring energy technology manufacturing infrastructure
We have incorporated the principle that securing access to critical energy infrastructure within the regional energy system by building up local manufacturing results in a short- and medium-term increase in cost of the energy infrastructure/ technology. One example is building alternative local/ national supply chains (e.g. for solar panels) to diversify and control a region's own supply chains and domestic manufacturing to reduce dependence on supplies from one region.

We are modelling the impact of reshoring energy technology manufacturing infrastructure as a cost increase of 10% on the capacity costs of wind (both onshore and offshore), solar, and Li-ion batteries in Europe and North America. The cost increase gradually rises from 2024 and reaches a maximum of 10% in the year 2030 before returning to regional cost curves by 2045. While these temporary cost increases have regional implications, the impact on the global costs of technologies and the direction of the energy transition is limited.

Regional restructuring of the global economy
There is an accelerating shift in sourcing and global manufacturing patterns to reduce dependence on a single manufacturing hub and boost supply chain resilience. For example, we are likely to see some production moving out of China to other neighbouring countries in South East Asia and the Indian Subcontinent. In other instances, domestic manufacturing strategies are pursued, combined with strategic trade partners; other upstream initiatives are aimed at securing access to raw material sources. All of this is reflected in moderately changing manufacturing volume effects in our model, where the manufacturing sector output is reduced in some regions and diverted to others. The impact on global manufacturing energy demand of volume shifts is minimal, as the carbon intensity of the regional manufacturing subsectors does not differ markedly and the diverted volumes relative to total manufacturing is small.
The impact in individual regions is low to moderate depending on the size of existing manufacturing sector volumes.

Conclusion
A shift towards protectionist industrial and economic policies that prioritize energy security, resilience, and independence could in theory accelerate the energy transition as countries invest more in locally-available renewable resources. However, it also risks promoting isolationist approaches that increase cost and hinder global cooperation in areas such as technology transfer, research and development, and coordinated climate action. In total, we find the sum of developments to slow the transition, as too many other shorter-term priorities move forward, and climate change implicitly moves backwards in the queue of priorities.

Highlights

This chapter outlines the Outlook projections on energy demand in transport, buildings and manufacturing sectors, highlighting a stabilization of energy demand amid growing economies, populations, and energy services.

In-depth sector coverage details sector-specific transition opportunities, infrastructure developments, and technology adoption determinants.

Both direct (e.g. EVs, heat pumps) and in-direct electrification (e.g. hydrogen and its derivatives) are portrayed as relevant for sectors such as manufacturing, aviation, shipping which are generally hard-to-electrify.

Technology shifts, energy substitution and efficiency gains are explained, including the role of AI, along with the impacts on conventional fossil energy consumption.

1

ENERGY DEMAND

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1 ENERGY DEMAND

The three main demand sectors – transport, buildings, and manufacturing – each use about 30% of the world's energy, with feedstock claiming the remaining 10%. Each sector's final energy demand has traditionally been strongly correlated with population growth and economic activity. Towards mid-century, this correlation will unravel; despite a significant rise in the demand for energy services, final energy demand will level off. Thanks to electrification and associated efficiencies, consumers will be getting a great deal more out of the energy delivered to their doors.

By 2050, we expect the global population to increase by about 20% to some 9.6 billion people. At the same time the global economy will almost double to USD 320trn, with an average global economic growth rate of 2.4% per year from 2023 to 2050 (see Appendix A.1 of this Outlook for further details on population and economic growth). As a result, the total amount of energy services required globally – measured in goods produced, km of transport, and square metres heated – will grow about 80% across the globe.

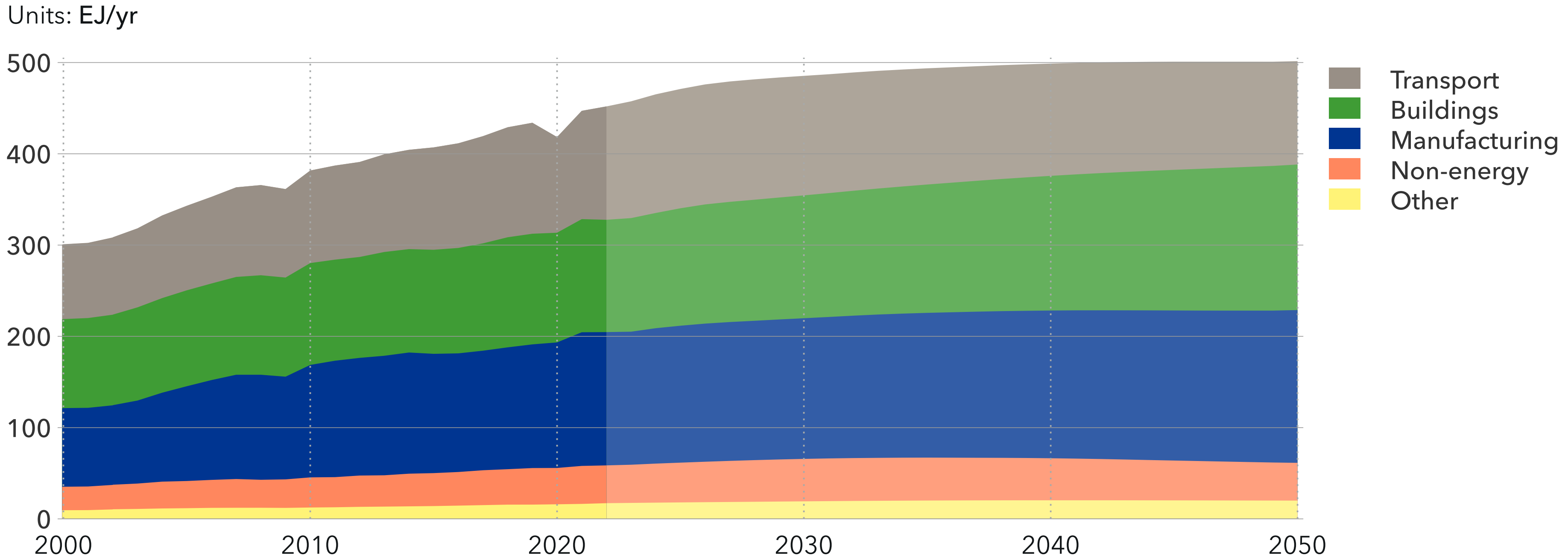
However, final energy demand will not grow at anywhere near 80% in the next two and half decades. Final energy is commonly understood to be the energy that reaches the consumer's door and is then used by the consumer (e.g. households, transport, factories) for their energy end-uses. Final energy demand will in fact only grow 10% from 455 EJ to 502 EJ between now and 2050 (Figure 1.1). Moreover, in the decade before 2050, final energy demand is virtually flat, effectively levelling off at 2040 levels. This is because massive efficiency gains, particularly those enabled by electrification, will almost entirely offset the population and economic growth propelling demand for energy services (Section 1.5). The effect is strongest in transportation, where energy demand peaks in the late 2020s and reduces 15% towards mid-century.

It is not a given that final energy demand will remain flat after 2050. Once most energy services are converted to electricity, which automatically improves energy efficiency in most sectors, final energy demand may start to increase again until the global population peaks.

The key developments in the main demand sectors include the following:

FIGURE 1.1

World final energy demand by sector



Historical data source: IEA WEB (2024)

Buildings energy use for space cooling will more than triple, while space heating demand will decline somewhat due to new technologies like heat pumps reducing energy needs. Overall energy demand will increase 28% by 2050, representing 32% of global energy demand.

Manufacturing energy use will remain the biggest user of energy through the forecast period, with absolute energy use increasing 15% to 159 EJ in 2050. Substantial efficiency gains and increased recycling moderate the increase. The feedstock sector will see energy demand grow modestly and peak in the mid-2030s before returning to present levels.

Road transport sector will see the strongest shift to electricity and therefore also the strongest efficiency gains. While aviation and maritime cannot electrify similarly, global transportation energy demand peaks before 2030. By 2050, it reduces to a level 12% lower than today which will represent less than a quarter of global energy use.

Although final energy demand will level off globally, this is not the case for all regions. In Europe and OECD Pacific, energy demand has already peaked, while energy demand will continue to increase through to 2050 in many of the middle- and low-income regions. Greater China's share of global energy demand is currently 25% but will decline to about 20% in 2050. The Indian Sub-continent will overtake North America as the second largest energy consuming region around 2040.

> Final energy demand will grow by only 10% from 455 EJ to 502 EJ between now and 2050, while demand for energy services required globally will grow by 80% over the same time period.

Final energy demand

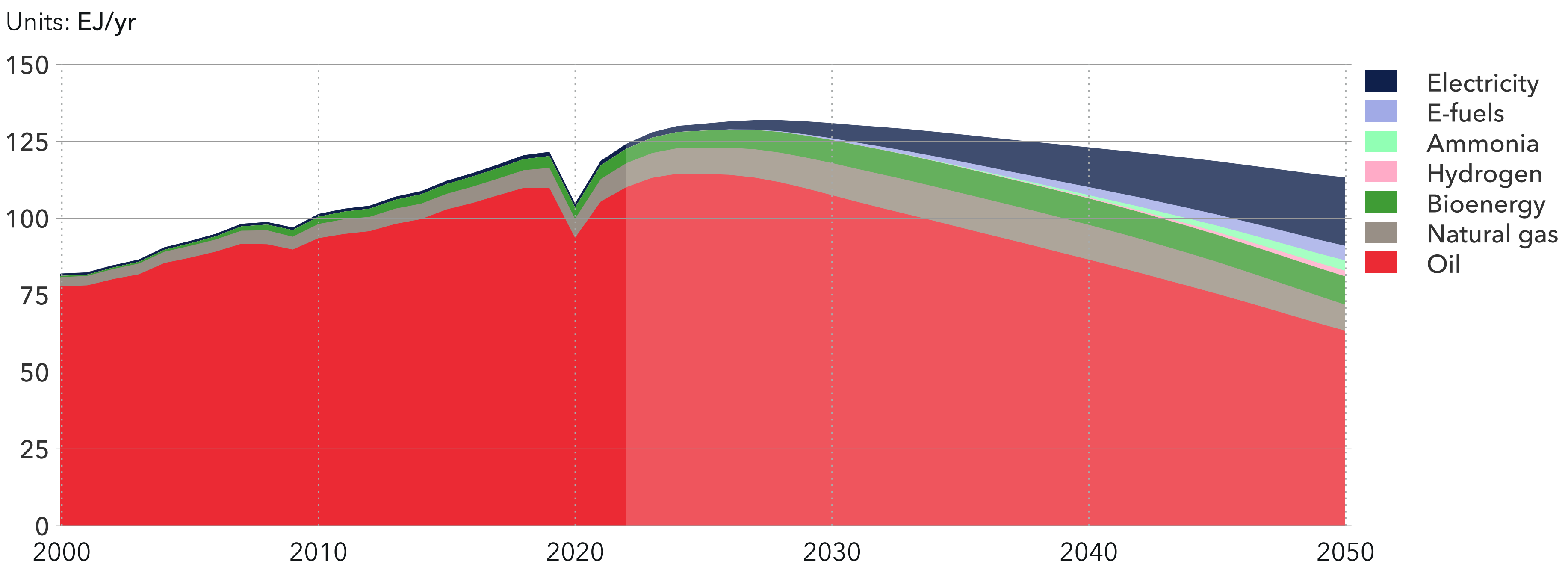
In this Outlook, we define 'final energy demand' as the energy delivered to end-use sectors, excluding losses (for example, heat losses in thermal power plants) and the energy sector's own use of energy in power stations, oil and gas development, processing, and transport infrastructure (Figure 1.1). Final energy is effectively the energy delivered to the consumer's door that is then used to power end uses (e.g. in households, transport, and factories).

1.1 TRANSPORT

Transport energy demand will reduce slightly from now to the mid-century, from 128 EJ/yr in 2023 to 115 EJ/yr in 2050. This 9% reduction occurs despite an increase in passenger and freight travel demand, higher car ownership, and more and more e-commerce/consumption. It is made possible by the deep electrification of road transport that is already under way in some major economies and which we forecast to also become the norm in the remaining regions. Post-pandemic resurgence in air-travel will lead to 60% higher aviation energy demand in 2050 compared with 2023, linked to higher levels of prosperity. Maritime trade will also expand even as the world becomes more multipolar and the 'slowbalization' trend deepens, leading to a growth in maritime energy demand despite ongoing efficiency gains in the sector.

FIGURE 1.2

World transport energy demand by carrier



Historical data source: IEA WEB (2024)

Global transport energy to 2050

In 2024, the transport sector is the single largest consumer of oil in the world, accounting for 65% of the oil demand. While this will reduce to 57% by 2050, oil will still be the largest energy provider of transport around the world (Figure 1.2).

From an inconsequential share (about 1%) in the energy mix in transport today, electricity will make up almost one-fifth of the total energy demand by mid-century. We forecast rapid road sector electrification through EVs, first in passenger transport and then in the heavy commercial vehicle segment. Not only will EVs eliminate tailpipe emissions, they will also contribute to efficiency gains because of the high-exergy characteristic of electricity. This will lead to overall energy demand reduction.

The need to combat local air pollution and global CO_2 emissions has given impetus to the use of biofuels and natural gas. Biofuel will be used in both its pure form and as a blend with gasoline and diesel. Most of the present use of natural gas in transport is in road transport, but given the decarbonization objectives of the maritime industry, we foresee the global use of natural gas split equally between road and maritime transport by 2050. We forecast a similar trend for bioenergy/biofuels.

In 2023, most of the biofuels in the transport sector were used in road transport. However, decarbonization objectives of the hard-to-electrify maritime and aviation sectors will also drive up the demand for biofuels in those segments. At the same time, biofuel use in road vehicles will decline as electrification of road transport deepens. By 2050, we foresee almost 60% of biofuels for transport will be used in the aviation sector.

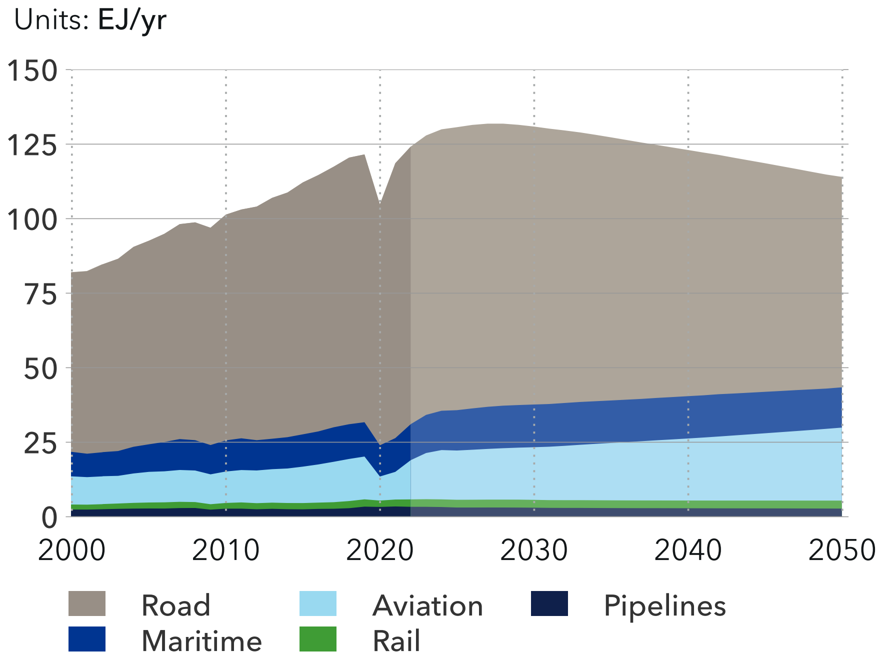
Sustainable aviation fuels (SAF) will see increased uptake starting in the 2030s and by 2050 will account for 12% of world aviation energy demand. Similarly, ammonia and methanol will also see increasing uptake in the maritime sector from 2030s. Together these two fuels will make up 37% of the maritime energy demand by 2050.

Our forecast does not foresee a significant share of pure hydrogen in world transport energy demand; it will see a mere 2% share by 2050, mostly in commercial fuel cell electric vehicles (FCEV) and some use in aviation, rail, and maritime.

The total energy mix (Figure 1.3) shows how road transportation energy use shrinks due to extensive electrification while maritime remains fairly stable and aviation energy demand expands. Road transport's share of transport energy demand reduces from 75% in 2023 to 61% by 2050 and in absolute terms from 94 EJ/yr to 71 EJ/yr. Figure 1.3 masks profound energy mix changes within each sector.

FIGURE 1.3

World transport sector energy demand by mode



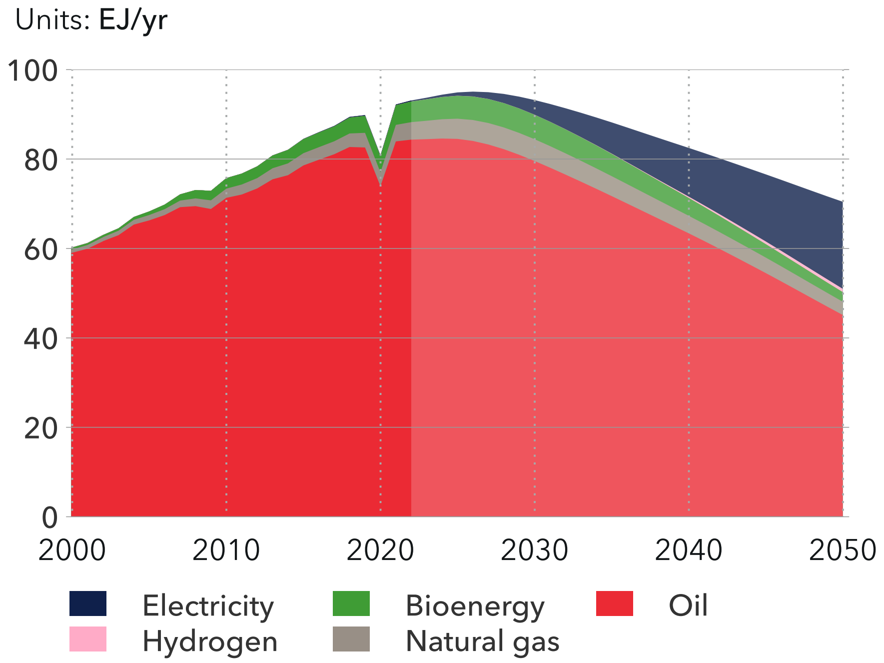
Historical data source: IEA WEB (2024)

Rising prosperity and the corresponding rise in personal disposable income in many world regions, such as the Indian Subcontinent and South East Asia, leads to increasing demand for air travel and an increase in aviation energy demand despite the energy efficiency gains which are continuously made in the aviation industry.

We do not see a drastic modal shift in transport choices across the world, although there are some regional differences. In many wealthy regions, as well as regions dominated by emerging economies, aviation will start encroaching on the road sector's share of transport energy demand.

FIGURE 1.4

World road energy demand by carrier



Historical data source: IEA WEB (2024)

Road

Road energy demand was by far the biggest contributor to transport energy demand in 2023 (75%). However, by mid-century, road transport's dominance in transport energy demand will have ended in some regions – notably in North America, Europe, and Greater China. We estimate that by 2025, Greater China's aviation energy demand will actually be slightly larger than its road energy demand because demand road sector flattens due to electrification while the number of flights (not electrified) expands. We expect road energy demand to reduce from 94 EJ in 2023, to 70 EJ by mid-century, a 1% reduction year-on-year, brought on by the deep electrification in passenger and then commercial transport.

At present, 90% of the road energy demand is supplied by oil with small amounts supplied by natural gas and biomass (Figure 1.4). We forecast that the substantial electrification in the road segment in the next three decades will eat into this dominance and by mid-century oil will only have a share of 64%. Our 2050 projections are that oil will only power 38% of passenger vehicles and just over 60% of commercial vehicles in 2050. Electricity will provide a higher than proportional share of road trips due to its better fuel/energy efficiency compared with oil.

Deeper electrification also implies that biofuels and their share in road energy mix will also correspondingly decrease, both as a share (from 5% in 2023 to 3% by mid-century) and in absolute terms. We do not forecast a significant uptake of hydrogen-based FCEV at a global scale; hydrogen will only make up 1.5% of total road energy demand by 2050. Most of the hydrogen that is used will be in heavy trucks to move goods over long distances in regions where geography and infrastructure make hydrogen a viable alternative, such as North America, or where strong support for hydrogen exists, like Japan.

We divide the road transport sector into three categories: passenger vehicles, commercial vehicles, and two- and three-wheelers (a significant category in the regions Greater China, South East Asia, and the Indian Subcontinent). 'Passenger vehicles' encompass those with three to eight passenger seats. This includes most taxis, excludes buses, and (solely in the case of North America due to the region's affinity for them) includes pick-ups.

'Commercial vehicles' comprise other non-passenger vehicles with at least four wheels and are particularly prominent in lower-income and emerging economies. However, as these countries and regions experience economic growth, and the population experiences upward mobility, passenger vehicle ownership goes up, thus stabilizing the share of commercial vehicles in the fleet.

> Half of new passenger vehicle sales will be electric by 2031.

Estimating road transport energy demand

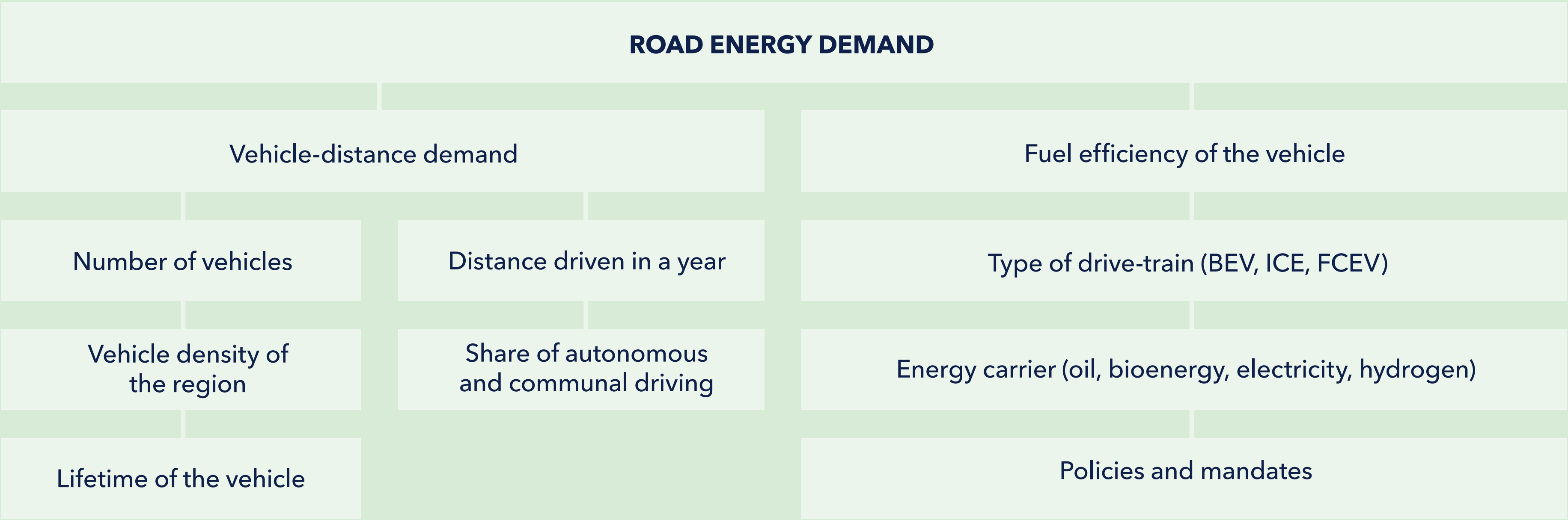
We estimate the world's vehicle fleet (including two- and three-wheelers) will grow from 2.3 billion vehicles in 2023 to a plateau of 3.5 billion vehicles in the 2040s. How does one calculate the energy demand from this growing and changing fleet? In our forecast, road energy demand for each region is primarily driven by the vehicle-distance demand (given in vehicle-kilometres) and the fuel efficiency of the vehicle. Vehicle-distance demand is in turn driven by the number of vehicles and the distance driven in a year (Figure 1.5).

Vehicle-distance demand: vehicle-distance demand is the product of the number of vehicles on the road in a given year and the average distance driven in a year by each vehicle. Each of these factors are themselves determined and impacted by developments in the future. Vehicle-distance demand multiplied by energy use per vehicle-distance gives the energy demand for road transport.

Number of vehicles: GDP per capita is a driving force behind vehicle density and ultimately the number of vehicles. This link is influenced by various factors such as geography, culture, technology affinity, infrastructure, environment, and the presence of alternative modes of transport. To forecast future vehicle density trends, we have utilized historical data fitted to a Gompertz curve (a type of S-shaped curve) (Figure 1.6). Wherever historical data is lacking to provide an accurate estimate, we set the model parameters to allow adjustments for the impact of policies promoting alternatives to road transport.

FIGURE 1.5

Determinants of road energy demand



The second determinant of the number of vehicles is the lifetime of vehicle. This differs from region to region and is based on the economic ability of the populace to change/upgrade to new vehicles.

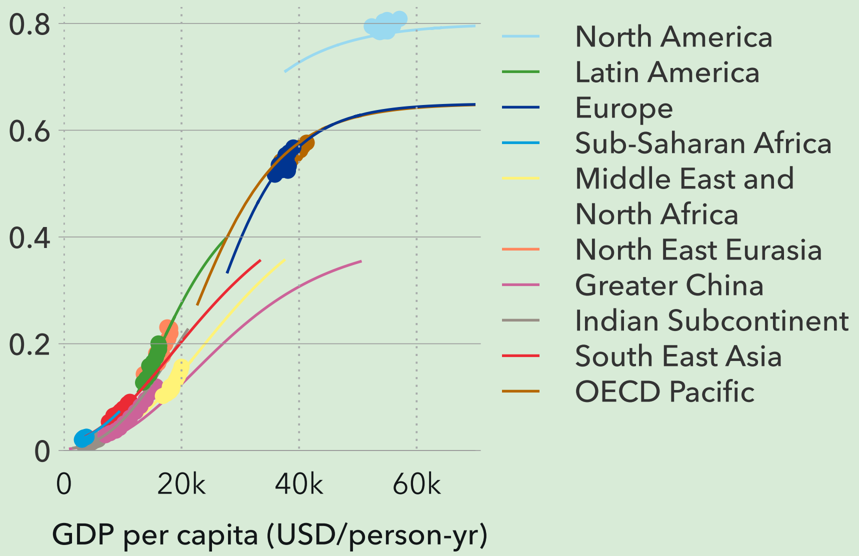
Distance driven in a year: The distance driven in a year in the future will be impacted by two major trends. The first of these is the rise of communal use of passenger vehicles, such as platform-based ride-sharing services in advanced economies. While communal use of passenger vehicles and lower ownership are commonplace in emerging economies, with advances in digital technologies and software development, communal ridesharing has become very common in almost all countries and is taking ridership away from public transit. Furthermore, it is changing the distances driven by an average passenger vehicle.

Similarly, we also account for advances in automated driving capabilities in our projection of distances driven. While the automated driving revolution is significantly delayed compared to when its widespread adoption was expected just a few years ago, we do foresee its arrival increasing communal driving and exerting an upward force on distances driven in a year. We estimate that, depending on the region, automated and shared vehicles will drive between 20% and 90% more kilometres than a privately owned car.

FIGURE 1.6

Road vehicle density by region

Units: Vehicles per person



Points show historical data from 2005 to 2015 (OICA, 2016). Lines show model estimates from 1980 to 2050. Excludes two- and three-wheelers.

The impact of increasing automation is two-fold and in opposing directions in our forecast. Increasing automation increases the annual distance driven by a vehicle. Given the demand for vehicle-distance in a region is unrelated to automation, this implies that the demand for vehicles reduces. However, increasing automation also reduces the lifetime of a vehicle by 10% to 25%. Nevertheless, the net impact is that increasing automation will lead to a smaller number of vehicles overall.

Fuel efficiency of the vehicle: Fuel efficiency of a vehicle is dependent on the drivetrain of the vehicle and the energy carrier used. It is generally denoted as the energy used to travel a unit distance (MJ/km). In general, battery electric vehicles (BEV) are about 3 to 5 times more energetically efficient than internal combustion engines (ICE) and going forward, the fuel efficiency of the vehicle stock will have major implications for our forecast of transport energy demand. Thus, the uptake and adoption of EVs becomes critical to understanding how we see the transport energy demand evolving in the future.

Additionally, policies and mandates in countries and sub-national entities also drive the fuel efficiency of the different types of vehicles. One such example is the *Corporate Average Fuel Economy* (CAFE) standards of the US (Federal Register, 2023).

EV adoption mechanics

The adoption of EVs is well underway in many pockets of the world. There is greater proliferation in urban megacities of China and in the smaller countries in Europe. Norway leads by some distance, followed by Iceland, Sweden, and the Netherlands (IEA, 2024a). These front-runner markets saw early adoption drives in the 2010s characterized by tax subsidies for EVs and/or other benefits like lower toll and parking fees.

In the case of Greater China, EVs and their design and manufacture in the region have been a strategic priority for the government, which has invested heavily in the industry in recent years.

In many parts of the world, however, EVs remain not convenient enough or too expensive compared with ICE vehicles (ICEV) (Yang, 2023). Nevertheless, the calculus has been shifting in favour of EVs: over the last five years, the average range of EVs has risen from some 300 km to over 450 km (close to 300 miles) and lithium-ion battery pack prices have fallen by close to 50% (BloombergNEF, 2023). Competition between leading EV manufacturers has also intensified, exerting a downward pressure on EV prices which has stimulated adoption of EVs in most regions (Randall, 2024). However, in 2023, inflation, high interest rates, and the related cost of living crisis across OECD countries discouraged many car owners from switching to new EVs. Despite a sales slowdown for some leading brands – including Tesla and BYD – in the last 12 months, prevailing lower sales prices mean EVs appear to be poised for renewed growth (Ziady, 2024).

In our Energy Transition Outlook Model (ETOM), we explicitly model the uptake of EVs in the different regions based on the desirability of EVs versus conventional ICEVs. Desirability is a composite of three broad criteria: perceived utility of the drive-train, total cost of ownership, and network effects (Figure 1.7).

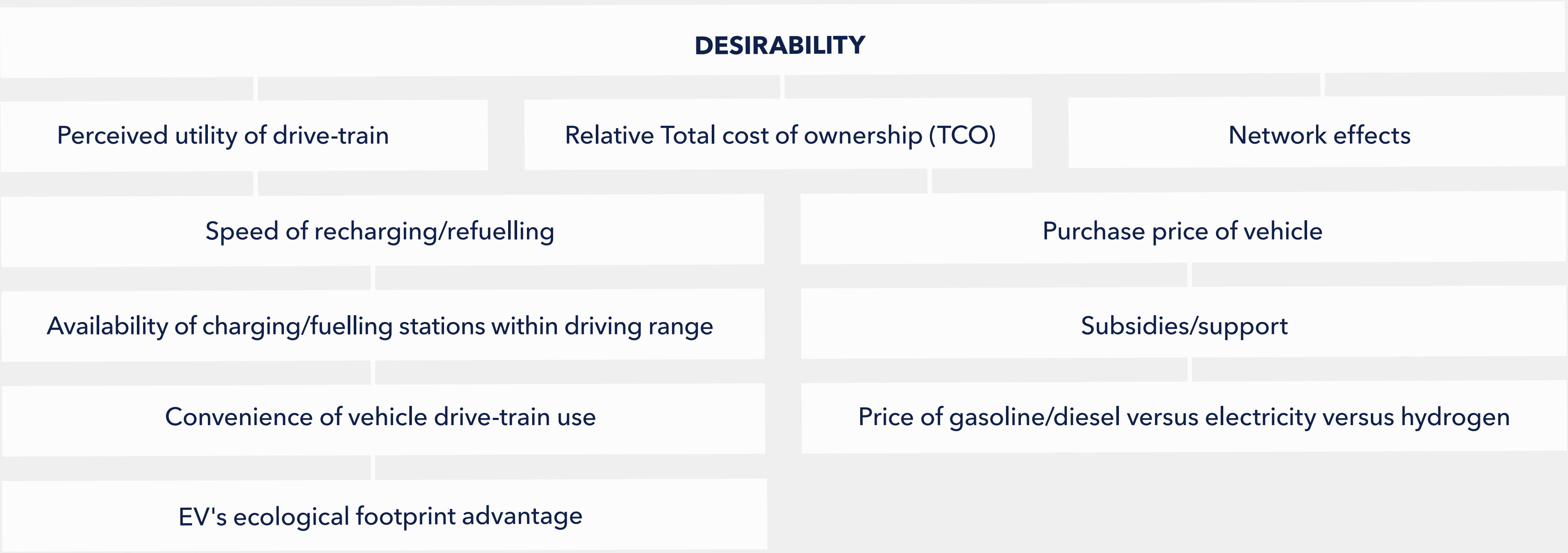
Perceived utility: The perceived utility of an EV compared to an ICEV is determined by the speed of recharging (fast charger availability), the density of charging infrastructure, the convenience of EV use due its ability to be charged at home, and the ecological advantage of EVs (which varies with respect to how clean the electricity grid is). All of these are important to varying degrees in the different regions but contribute towards the simulated purchase decision of an EV in our forecast.

Relative total cost of ownership (TCO): The TCO of a vehicle is the annualized cost of the vehicle, including its purchase price net of support/subsidies and the day-to-day running cost of the vehicle, i.e. energy use costs and maintenance. It should be noted that because EVs have fewer moving parts than an ICE, EV drivetrains are easier to maintain. We assume that in the case of passenger vehicles, the upfront purchase price has a higher weight within the TCO, while for commercial vehicles, which are generally subject to more rigorous financial analysis, running costs carry more weight in the purchase decision. We calculate the relative TCO as the ratio of an EV's TCO to an ICEV's TCO. A value less than one implies a lower relative perceived TCO for an EV which increases the EV adoption rates in the model.

Network effect: The network effect is commonly understood in relation to online platforms: when more people use a service, the value of the service for individual users tends to increase. A similar effect tends to characterize the adoption of EVs: a higher the number of adopters in a market causes the expansion of charging infrastructure in workplaces and other shared spaces which makes it more likely it is that more people will choose the technology. Over time, very high rates of adoption may lead to reduced availability of gasoline/diesel refuelling stations and repair facilities for ICEVs which in turn increases the adoption of the electric drivetrain.

FIGURE 1.7

Determinants of road energy demand



- **DESIRABILITY**
  - Perceived utility of drive-train
    - Speed of recharging/refuelling
    - Availability of charging/fuelling stations within driving range
    - Convenience of vehicle drive-train use
    - EV's ecological footprint advantage
  - Relative Total cost of ownership (TCO)
    - Purchase price of vehicle
    - Subsidies/support
    - Price of gasoline/diesel versus electricity versus hydrogen
  - Network effects

EV forecast

Based on our calculation of the EV adoption determinants, we forecast that EVs will be 50% of all passenger vehicles sold globally by 2031. Because battery sizes for commercial vehicles need to be larger, especially for long-haul vehicles, commercial EV adoption will lag passenger EVs. Commercial EVs will reach a 50% share of vehicle sales in 2039, eight years after passenger EVs reach that sales milestone.

Given the state of the electrification and related infrastructure in each region, the cost development of EVs, and the buying power of the population, EV adoption rates vary by region (Figure 1.8).

We project that EVs will comprise 50% of the new passenger vehicle market in Greater China and Europe by the late 2020s, followed by OECD Pacific and North America in the early 2030s. This implies that EVs will reach half of global new vehicle sales by 2031. This milestone is a key part of our forecast and has remained largely unchanged over the past five years, with actual EV uptake in recent years adding confidence to our forecast.

In lower-income regions, adoption will take longer due to limited charging infrastructure and fewer subsidies. However, even in regions with slower initial uptake, the 50% threshold will be reached by mid-century. By 2050, ICE vehicles will scarcely be sold in Greater China and Europe. In other regions, particularly North East Eurasia, ICEVs will still account for around 30% of new passenger vehicle sales.

The electrification of commercial vehicles will proceed more slowly than that of passenger vehicles. There are significant regional differences in the adoption of commercial BEVs. Greater China is expected to reach a 50% sales share for commercial EVs within approximately five years, followed by Europe two years later. However, North East Eurasia is not expected to reach a 50% sales share for BEVs within our forecast period (Figure 1.8).

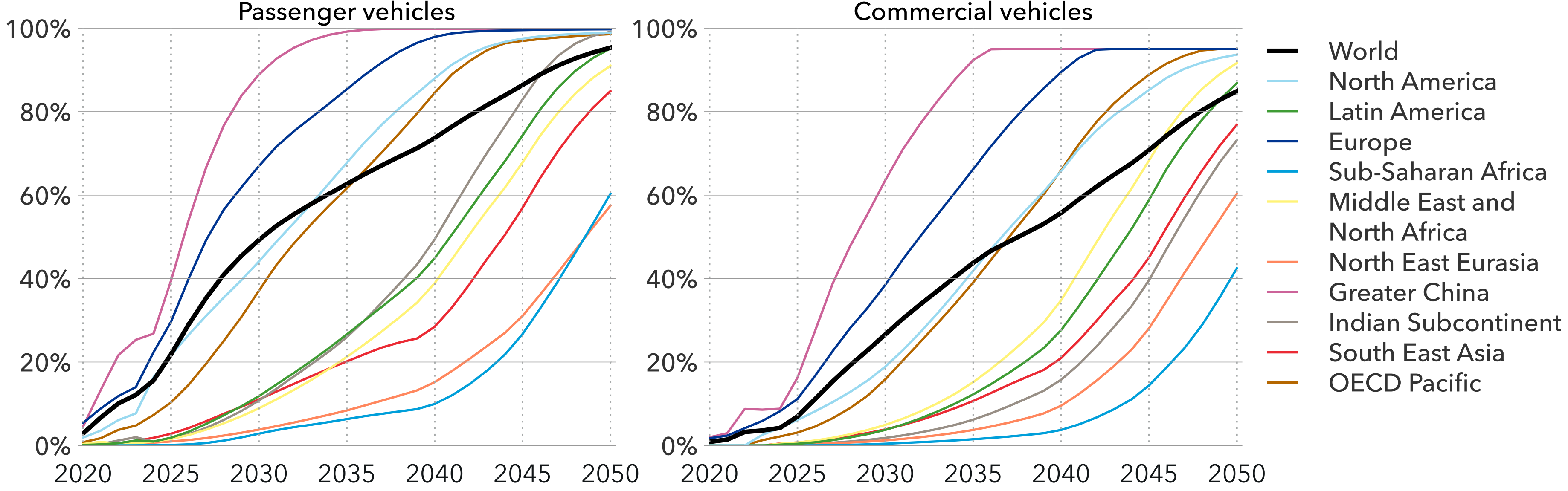
While commercial FCEVs will be important for heavy-duty long-haul trucking, electric solutions are advancing in this category faster than previously anticipated. Such a drastic increase in the share of EVs has significant impact on the stock of vehicles globally (Figure 1.9).

Due to saturation and automation of travel, we project the total number of vehicles will plateau by the mid-2040s at about 3.5 billion vehicles. Of these, more than half are going to be battery electric vehicles, with ICE vehicles only prominent in EV-uptake lagging regions such as North East Eurasia and Sub-Saharan Africa.

FIGURE 1.8

Market share of electric vehicle sales by region

Units: Percentages

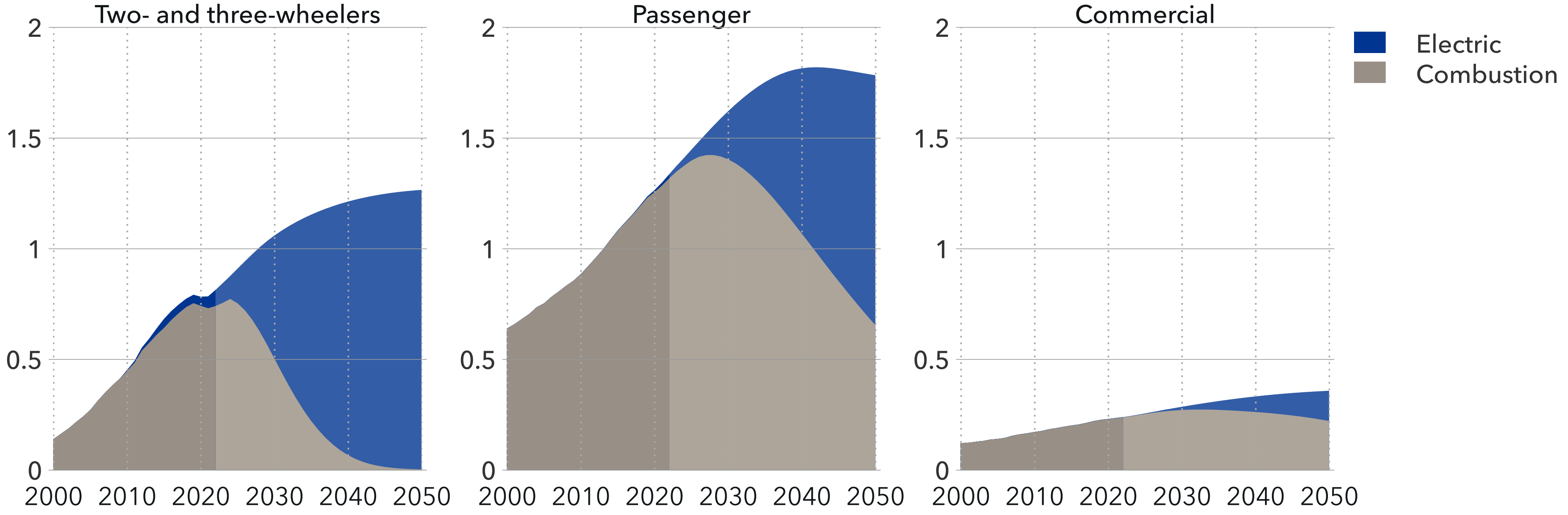


Electric vehicles include BEVs and FCEVs. Excludes two- and three-wheelers.
Historical data source: Marklines (2022), IEA EV Outlook (2023), EV Volumes (2022)

FIGURE 1.9

World number of road vehicles by type and drivetrain

Units: Billion vehicles



Note: Combustion vehicles include ICEs and PHEVs. Electric is >99% battery electric and <1% fuel cell electric.
Historical data source: Marklines (2022), IEA EV Outlook (2023), EV Volumes (2022)

In the passenger vehicle category, more than half of the vehicle fleet will be BEV by 2050. This does not hold true for the commercial vehicle category, where there will be slightly more ICE vehicles than BEV. The two- and three-wheeler vehicle category will be entirely electric by mid-century.

In lower-income regions, adoption will take longer due to limited charging infrastructure and fewer subsidies.

Resource limits on new capacity?

The rapid global adoption of EVs is a crucial aspect of the energy transition. We forecast a growth from today's EV fleet of 120 million vehicles (including two- and three-wheelers) to 2.5 billion in 2050. This represents an EV battery storage capacity of 130 TWh in 2050, a 50-fold increase compared with today's EV fleet. This poses a major challenge: securing a reliable supply of essential minerals, particularly cobalt, nickel, and lithium, which are critical for battery production. The increasing demand for these minerals has created significant pressure on the upstream supply chain, leading to price volatility and competition among companies and countries to secure these resources. So, can the supply of critical resources support the EV uptake we forecast?

At present, the global demand for cobalt from EV batteries is at 130 kt and given forecasts for changing battery chemistries and material efficiencies, by 2030 cobalt demand for EV batteries will be 280 kt/yr, growing to around 500 kt by 2050, a 6% average annual growth. The nickel demanded by EV batteries, on the other hand, is forecast to grow eight-fold, from around 330 kt in 2023, to around 1,100 kt in 2030, with demand reaching about 2,500 kt by 2050. The demand for lithium was at 110 kt in 2023 and is forecast to grow to 430 kt by 2030 and to 900 kt by 2050. The material demand forecast to 2050 is shaped by assumptions regarding EV battery chemistries, and is prone to uncertainty based on the proliferation of completely new battery chemistries (e.g. using sodium or potassium instead of lithium).

While these three critical materials all undergo surging demand, the energy transition we forecast will not be significantly constrained globally by the availability of these minerals or the scale up in mining and refining required. However, there are distinct regional imbalances in the availability of these minerals. Historically, such imbalances would be solved by global collaboration and trade. However, the intensified focus on national energy and resource security is likely to exacerbate existing imbalances and could affect costs in the short to medium term and thus warrants continuous monitoring.

The availability of these minerals and the mining and refining required do not place any significant constraints on the transition.

Unlike fossil fuels, there is no material loss during the battery lifetime, and all minerals can theoretically be recovered via a recycling process. As a result, recycling is an essential complement to the mined resources to secure a long-term sustainable supply of batteries. However, as we have shown in relation to Europe (DNV, 2024c), building a successful regional recycling system for batteries requires careful policy stewardship.

Note: resource requirements for the energy transition are discussed more fully in Appendix A.4.

Lithium mine, Chile

Rail

Rail transport is often overlooked, but it is a critical component of the transport sector. From moving crude oil and liquid petroleum gas (LPG) in the US (Association of American Railroads, 2023) to transporting coal for the power plants in India (IEEFA, 2023), trains move both freight and passengers in volumes that are often critical to national economies.

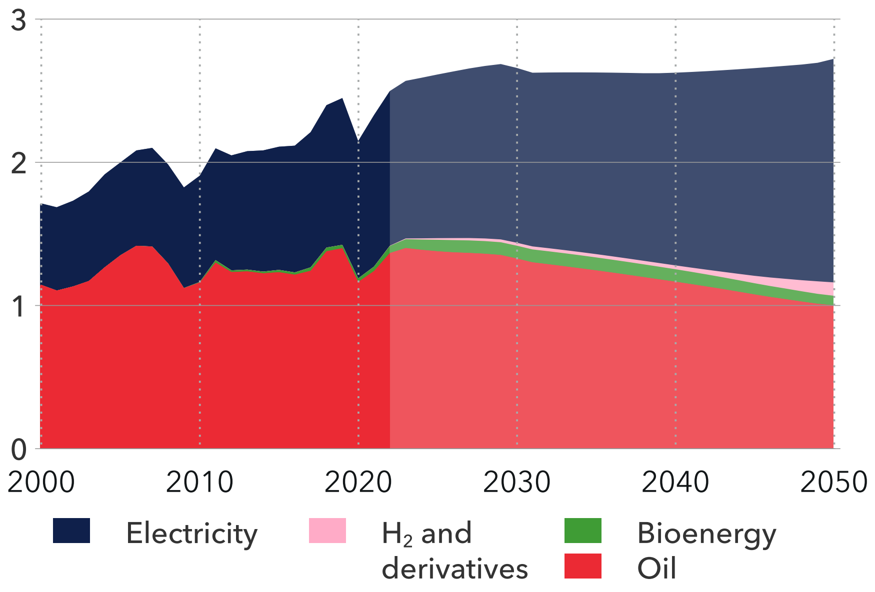
The total rail energy demand will stay about the same over our forecast period, only growing from 2.5 EJ/yr in 2023 to 2.7 EJ/yr by mid-century. This is despite a significant growth in rail such as new and improving high speed train services in regions like Greater China and South East Asia (World Bank, 2021). The long-term economic growth expected in all regions will see a doubling of rail passenger travel demand and a 60% growth in rail freight. The fact that these new volumes will require just 8% more energy by mid-century speaks volumes about the expected efficiency gains in rail transport, largely linked to deeper electrification. In relative terms, rail transport demand expands from 2% of total energy transport to 4% in 2050, with that expanding share largely explained by the decline in road transport energy demand.

In 2023, oil provided 55% of the rail energy demand but we forecast that this will reduce to 38% by mid-century (Figure 1.10). Deep electrification in regions such as Greater China, OECD Pacific, and the Indian Subcontinent (Ferris, 2024) leads to electricity overtaking oil as the primary energy carrier in rail transport by 2035.

FIGURE 1.10

World rail transport energy demand by carrier

Units: EJ/yr



Neglible amounts of natural gas and coal are not shown.
Historical data source: IEA WEB (2024)

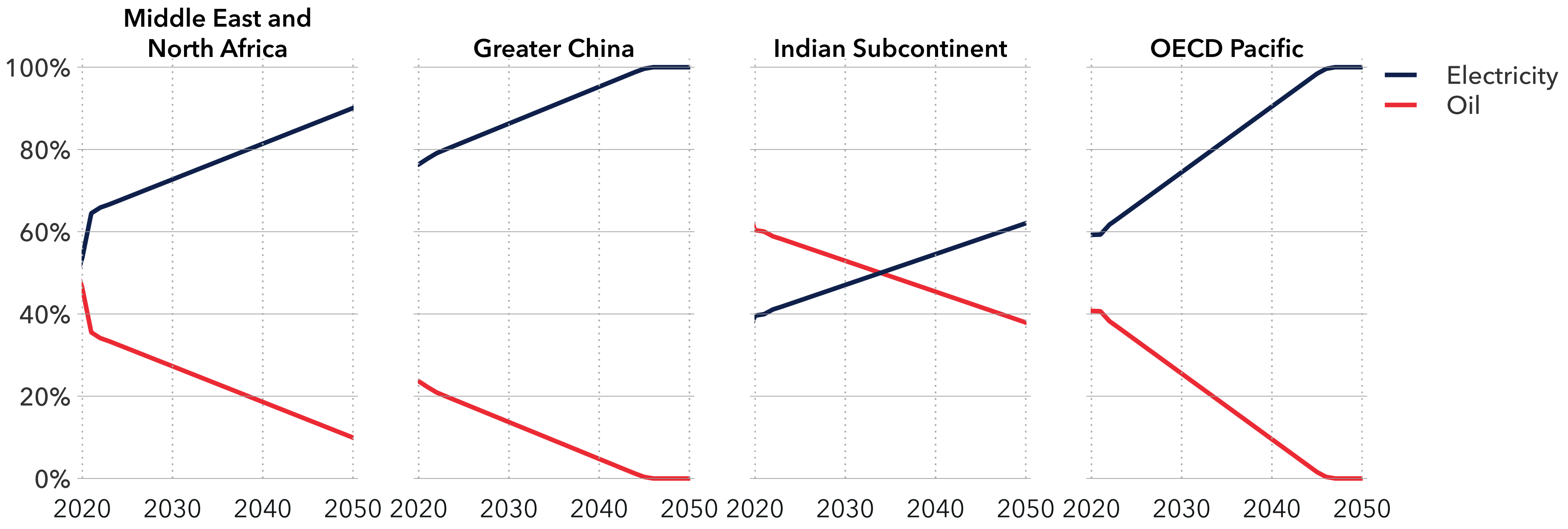
Regions have uneven starting points in their journey to electrify rail (Figure 1.11). In 2018, most trains across the Indian Subcontinent were running on almost exclusively imported oil with rail electrification at just 40%. This impacts foreign exchange balances and contributes to the deep energy insecurity of the region. In contrast, Greater China's rail transport was 80% electrified by 2018 thanks to the rapid proliferation of its high-speed electric rail network in the 2010s. We expect rail transport in Greater China and OECD Pacific to be fully electric well before 2050 while it will be 90% electric in the Middle East North Africa and only two-thirds electric across the Indian Subcontinent by then.

It is important to note that electrification is not the only decarbonization option and, in some cases, electrification may not even be the favoured option. How much rail can be electrified is dependent on many extraneous factors such as the regional terrain, engineering know-how, and willingness to electrify the entire length of the tracks. Most notably, the North American rail sector has faced hindrances to electrification from regulatory difficulties in electrifying tracks to inability to procure land for development of tracks/lines (Hoecker et al., 2023). As such, we foresee a combination of options – such as hydrogen, biofuel, and even e-fuels – making inroads in the future in the shift away from oil in rail in North America.

FIGURE 1.11

Share of oil and electricity in rail energy demand in selected regions

Units: Percentages



Aviation

The temporary drop in aviation energy demand caused by the pandemic was mostly nullified by 2023. Energy demand for aviation is now poised for an expansion of some 60%, from 6 EJ/yr in 2023 to about 25 EJ/yr by mid-century (IATA, 2024).

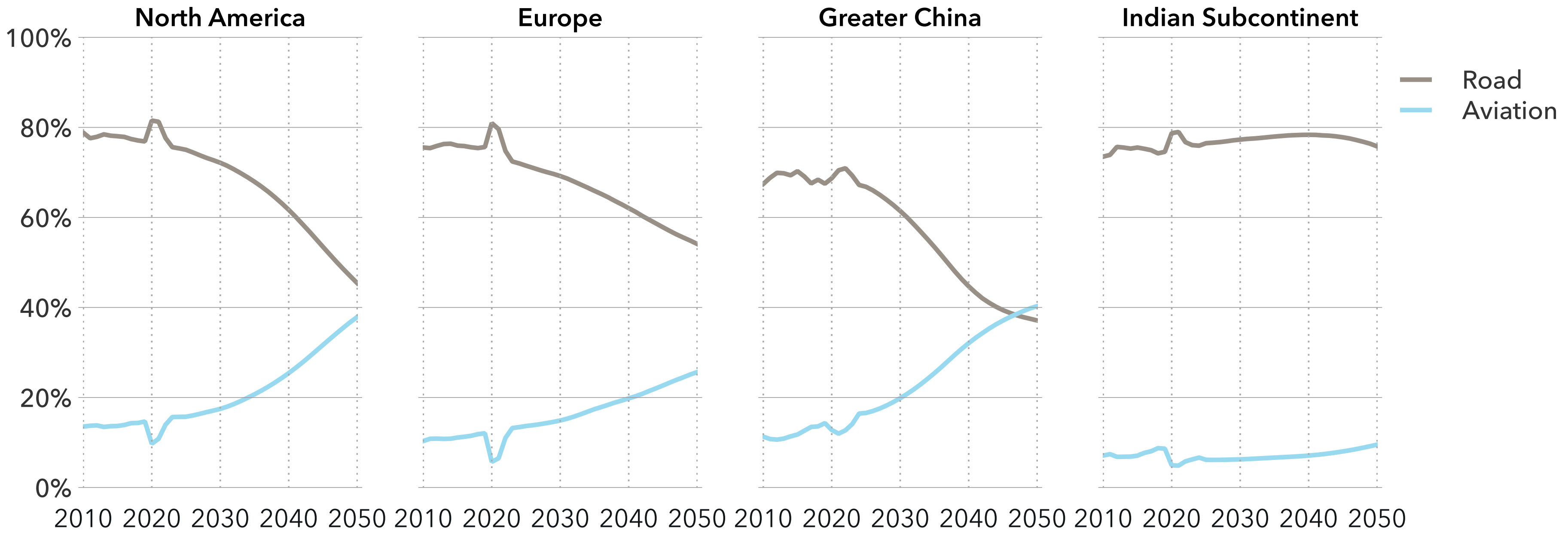
Overall energy demand will expand more slowly than global passenger flight demand, which is forecast to double from 4.3 billion person-trips/yr to 8.6 billion person-trips/yr by 2050. Much of this expansion in person-trips is due to increasing demand from countries where there has historically been little to no personal disposable income for flights. Aviation demand across Greater China expanded almost 10-fold between 2000 and the present. While future demand in China is expected to be much closer to the global average, countries like India, Indonesia, and Vietnam are poised for significant growth.

The phenomenon of 'flight shame' that took root before the pandemic has not spread across the world the way it did in parts of Europe. While it may have a damping effect on flying for holidays, research has shown that it has lesser impact for travel related to work or visiting family. More importantly, 'flight shame' has not had a significant impact in the developing world (Doran et al., 2022).

FIGURE 1.12

Share of road and aviation energy demand in transport

Units: Percentages



The rise of aviation travel demand can be best understood by looking at the aviation versus road sector share of transport demand in the past and future for selected regions. In the case of Greater China, aviation energy demand grows to surpass road sector energy demand by the mid-2040s. Across almost all regions, the aviation share of transport demand grows while road transport falls by mid-century (Figure 1.12). The two main reasons for this happening are: rising demand for flights, especially overseas passenger flights, due to rising prosperity levels, and road transport energy demand decreasing due to very high electrification levels. It should be noted that the aviation energy share includes both cargo and passenger demand. Passenger aircraft greatly outnumber cargo aircraft, and it is passenger aviation demand, driven in turn by rising incomes, that has the main impact on forecast aviation demand.

In a similar vein to Greater China, we see North America's aviation energy demand almost equalling road transport demand by mid-century. In Europe, the two lines do not converge as forcefully: Europe has only a relatively moderate share increase of aviation energy demand (13% in 2024 to 26% by mid-century). This is due to the moderate growth in passenger aviation demand in Europe and also local policies incentivizing rail travel over shorter distances (Ros, 2023).

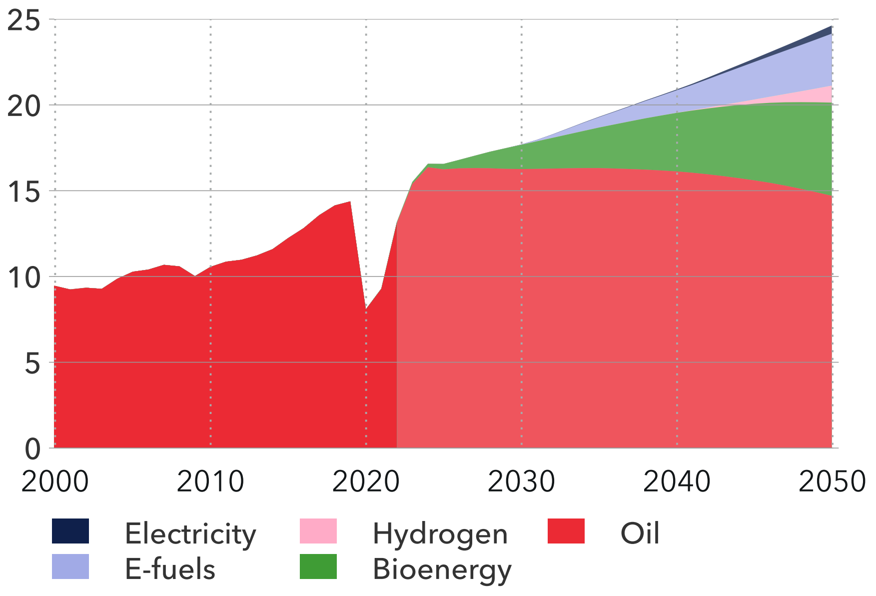
In 2023, almost all of the energy demand in aviation was supplied by oil (Figure 1.13). By mid-century, we expect oil's share to decrease to 60%, with electrification having a minimal impact and biobased SAFs taking the majority of the share relinquished by oil.

Despite a manageable number of stakeholders and an international governance framework, the decarbonization drive is primarily delayed due to electrification not being widely adoptable. Electrification is viable mainly for short-haul flights due to battery weight. When it does start, we expect electrification to begin with small commercial aircraft before 2030 and then gradually expand to larger short-haul planes in the 2030s. However, due to the low energy density and the fact that most fuel is used on long-haul flights, we forecast batteries to account for only 2% of aviation fuel by 2050.

FIGURE 1.13

Aviation energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2024)

> We expect electrification to begin with small commercial aircraft before 2030, gradually expanding to larger short-haul planes in the 2030s.

Aviation industry players are instead presently exploring two alternative pathways to decarbonize the aviation sector while still meeting demand: pure hydrogen and SAF. While hydrogen offers near emission-free transport, its low energy density requires new aircraft designs and infrastructure. This will limit its adoption to 4% of the energy mix by 2050. We expect Bio-based SAF – driven by its more widespread availability, first mover advantage, and having less regulatory barriers to being certified as renewable fuels – to reach a 22% share by mid-century. SAF in the form of e-fuels based on hydrogen will gain traction in the 2040s. We project E-fuels to dominate over pure hydrogen due to their versatility, reaching a 12% share by 2050.

Even as demand grows, efficiency gains and fuel mix changes position aviation to surpass the partial decarbonization goals set by the *Carbon Offsetting and Reduction Scheme for International Aviation* (CORSIA) by 2050. However, those goals fall well short of fully decarbonizing the segment. Additionally, mechanisms such as the *RefuelEU Aviation Initiative* (European Council, 2023), which aims to increase the uptake of SAF as part of the wider *EU Green Deal*, play a critical role in adoption of SAF and creating a viable customer base for the production/consumption of hydrogen-based fuels. The voluntary carbon market, whose participants comprise service sector corporations such as financial institutions and information technology giants, are willing to invest in SAF to various degrees in order to reduce their Scope 3 GHG emissions. However, at present such voluntary carbon reduction efforts are still in their nascent stage.

A potential impact of the growing integration of expensive SAF into the aviation energy mix (currently somewhere around double the cost of jet fuel) is an increase in the cost or price of air travel, with these expenses likely being transferred to passengers under the 'polluter pays' principle. Passenger demand for air travel is closely tied to costs, particularly as it relates to disposable income. If aviation companies are required to meet stringent emissions targets and consequently pass on the added cost of SAF to their customers, this could serve as a moderating factor on the rising demand for air travel, particularly in regions experiencing new growth. For this iteration of the forecast, we have not factored in this potential balancing effect but we will continue to closely monitor developments in the aviation sector.

A further factor affecting aviation demand is AI and its use in commercial organizations. According to estimates by Goldman Sachs, generative AI could automate activities that amount to the equivalent of 300 million jobs across the world (Hatzius et al., 2023). It stands to reason that an upheaval on this scale could affect business travel in the longer term. While business travel is responsible for only 20% of the travel volume, business class travel produces most profits for airlines, and AI may therefore disrupt the aviation business model in the future.

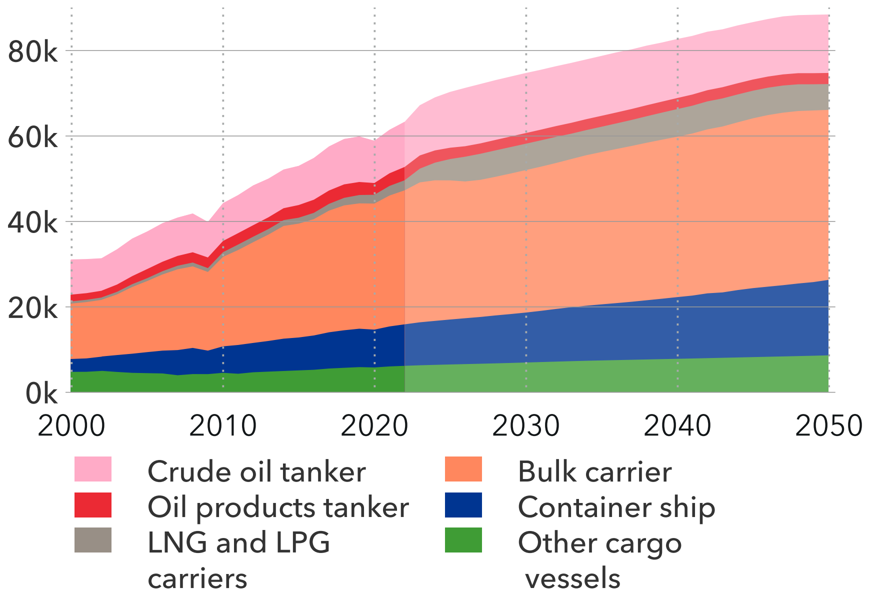
Maritime

We forecast maritime energy demand will only grow slightly, from 13 EJ/yr in 2023 to 14 EJ/yr by 2050. More extensive and effective energy efficiency measures – for decarbonization purposes, meeting energy efficiency standards, and cutting costs – will temper energy demand growth in the maritime sector. Although cargo-tonne-miles are projected to increase, the decarbonization of many demand sectors globally will curb and ultimately reverse the growth in seaborne transport of coal, oil and, later, natural gas. Our forecast of maritime energy demand is first and foremost influenced by our expectations of maritime/seaborne trading of goods, as passenger transport is a minor contributor to maritime energy use, setting maritime apart from other transport modes in this respect.

FIGURE 1.14

World seaborne trade in tonne-miles by vessel type

Units: Gt-nm/yr



Historical data source: Clarksons Research (2021)

Global cargo shipping is a fundamental aspect of our analysis. The regional dynamics of fossil-fuel demand and supply dictate that any imbalances are resolved by transporting excess resources from surplus regions to deficit regions. Moreover, significant maritime transportation of fossil fuels takes place within individual regions. Similarly, the movement of raw materials and finished goods occurs both within and, notably, between regions.

In a world where GDP doubles by 2050, the demand for cargo transportation will outweigh efficiency gains. Consequently, we project cargo tonne-miles to rise across most ship categories (Figure 1.14), with a total growth of 40% from 2023 to 2050.

This growth is unevenly distributed among ship and cargo types. Container transport has long been the main growth engine and this will continue with an expected 80% growth in tonne-miles to 2050. Part of this is due to containerization, where more and more types of cargo are transported in containers. Certain bulk segments, such as grain and minor bulk, are also growing, as is LNG transport. In other sectors, efficiency improvements and global trade pattern changes will lead to reductions. The drastic reduction in coal demand, thanks to dwindling coal demand in the power sector in countries such as China, will result in a halving of maritime coal transport. Similarly, deep electrification of the road transport has second-order impacts on both sea-borne crude oil and oil products transport, leading to a 20% reduction by 2050.

In addition to the economic drivers, we observe several short- and long-term trends influencing our forecast of world seaborne trade:

- In the short term, we observe certain seaborne trading routes coming under intense pressure from conflict activity – such as the attacks on commercial shipping in the Red Sea – and from climate change-related extreme events – such as the drought affecting the Panama Canal and disrupting water-borne trade between North and South America. All these disruptions serve to increase seaborne trade distances and increase the need for maritime transport.

- In the short to medium term, we see the world moving from globalization to more regionalization and multi-polar priorities whereby some regions are increasing their efforts to reduce dependence on raw materials and goods from regions outside their sphere of influence. This implies disruptions in well-established seaborne trading patterns and the establishment of new patterns. For example, when Russia invaded Ukraine, it disrupted piped natural gas to Europe from Russia. While this led to more LNG export from the US and Canada to Europe, it also resulted in more oil moving from Russia to China and India.

- In the longer term, protectionist policies enacted by some countries/regions to safeguard their industries will also lead to reduced trade.

These factors depend on how the geopolitical forces take shape and what the near-term trade equilibrium looks like. They therefore add to the uncertainties of maritime trade.

In the coming years, transport on keel will become more expensive due to an increasing share of low-emission fuels in the maritime fuel mix. This might impact established transport routes in cases where domestic production has an advantage over higher-priced transportation.

Maritime fuel mix

The maritime sector is still regarded as a hard-to-abate sector. However, the regulatory push from the International Maritime Organization (IMO) and the EU, as well as demands from leading charterers for lower-emission transport, are rapidly driving the sector's focus, ability, and enforcement of decarbonization.

As electrification options are limited to port-stays and short routes, decarbonization alternatives for maritime fuel will all come at a significant cost increase, estimated at about a 70% to 110% increase in total cost of transport (DNV, 2024b). Expensive fuel alternatives encourage further focus on energy efficiency and might, to a limited extent, influence freight volumes. The main result of this will be an increase in freight rates with costs moving to consumers by means of a modest increase in the price of goods.

IMO's decarbonization strategy is ambitious, aiming for 'net-zero emissions by or around 2050', and reductions from 2008 levels of 20% to 30% in 2030 and 70% to 80% in 2040. A lack of enforcement mechanisms makes the full achievement of this strategy unlikely and neither strict EU regulations nor charterer push are sufficient for a global implementation to achieve these targets. Nevertheless, the industry is rapidly moving towards decarbonization and this outlook includes a trajectory with 20% reduction in CO_2 emissions to 2040 and 60% reduction to 2050, compared with 2023 numbers. Unlike many other demand sectors, there is significant uncertainty in which technology and fuel options will ultimately win the maritime decarbonization race.

As all fuel options are expensive, a very interesting alternative is continued use of oil with onboard CO_2 capture. Despite additional fuel use and assuming a moderate capture rate of around 75%, this option is less expensive than advanced biofuels, methanol, or ammonia (DNV, 2024b). However, its success is dependent on a global shore-based receiving mechanism with subsequent coupling to a transport and storage network. The latter will be developed in most regions regardless of shipping (Section 7.2).

DNV's best estimate of maritime fuel mix includes gradual phase-in of onboard CCS from 2040, encompassing 15% of all fuel in 2050 (Figure 1.15). A capture amount of 120 $MtCO_2$ from shipping corresponds to about 8% of all CCS globally.

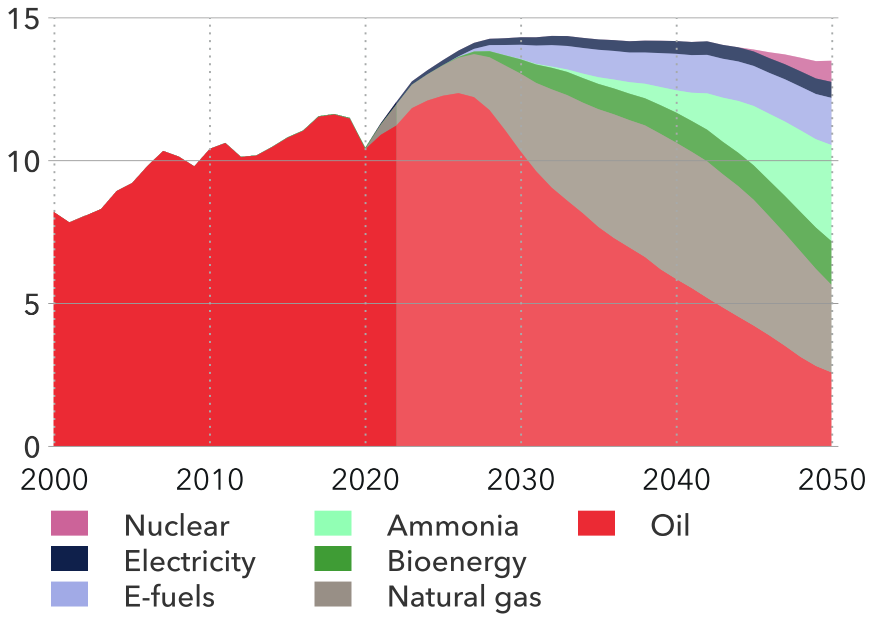
Also new in this year's fuel mix is the opportunity of nuclear shipping. Small modular reactors (SMR) on board a ship present a potentially attractive no-refuel-through-vessel-lifetime option (SMR is described in more detail in Section 3.4). Unlike onshore, onboard nuclear competes with expensive biofuel and e-fuel options rather than cheap power from solar and wind. Nevertheless, the technological, commercial, and regulatory challenges to onboard nuclear remain considerable. Hence, we include nuclear propulsion only from 2045 in our Outlook, comprising 6% of maritime fuel mix in 2050.

Shifting away from its predominately oil-based fuel mix today, a significantly decarbonized maritime 2050 fuel mix is dominated by hydrogen-based fuels with 24% ammonia and 12% e-fuel (likely methanol) with an addition of 11% biofuel (Figure 1.15). Electrification will be low (4%) although it may dominate the smallest ships sailing short routes. Natural gas will continue its growth towards 2040, but towards 2050 will likely reduce again as its CO_2 content is too high for deep decarbonization.

FIGURE 1.15

Maritime energy demand by carrier

Units: EJ/yr



Natural gas includes LNG and LPG. Historical data source: IEA WEB (2024)

Our fuel mix forecast for maritime is a result of our best estimate assessment and not the result of a cost competition-based model output. It indicates that our view on the maritime fuel mix to 2050 holds significant uncertainties, partly described above and detailed further in DNV's *Maritime Forecast to 2050*.

> As all decarbonized fuel options are expensive, a very interesting alternative is continued use of oil with onboard CO_2 capture.

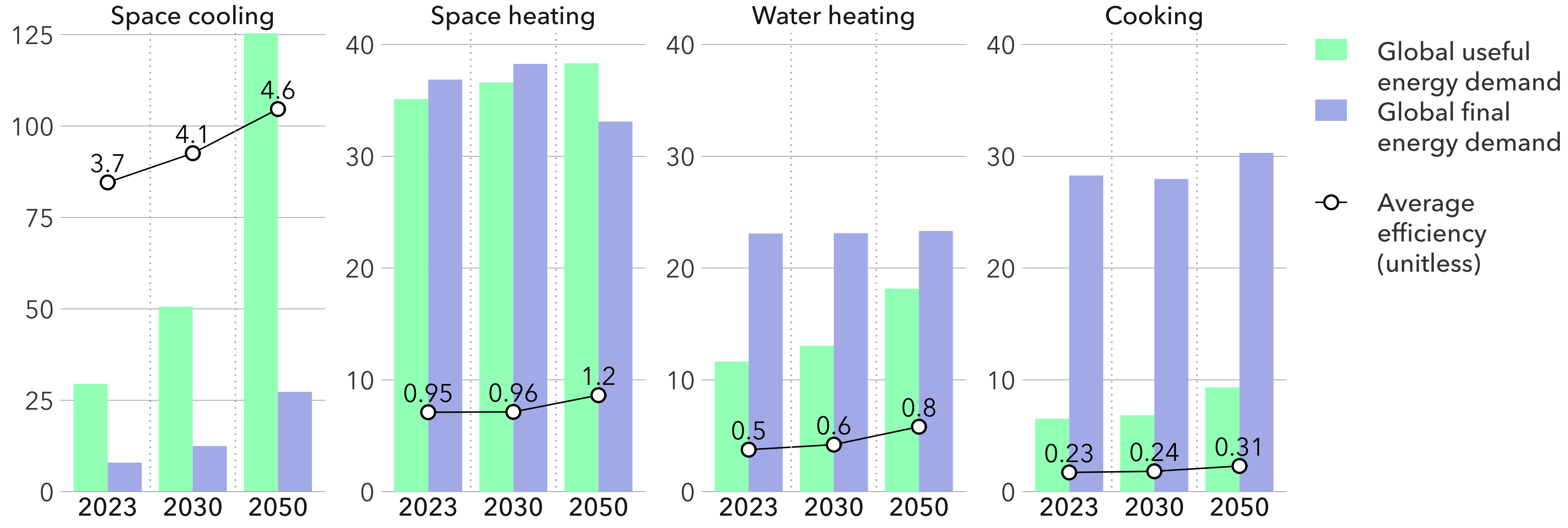
1.2 BUILDINGS

Despite increasing electrification and improvements in the efficiency of thermal insulation and heating/cooling equipment, global energy demand for buildings is set to grow nearly 30% over the next three decades, from 124 EJ per year in 2023 to 160 EJ per year in 2050. The sector's share in final energy demand is also expected to grow from 27% in 2023 to 32% by mid-century. The main drivers for these increases are a growing population requiring more floor area coupled with rising GDP per capita incomes leading to a growing demand for space cooling – exacerbated by climate change – and other electric appliances. These trends in population, incomes, and rising temperatures would result in explosive energy demand growth in the buildings category if it were not for the significant energy-efficiency gains we expect during our forecast period.

FIGURE 1.16

Buildings useful and final energy demand and efficiencies of various end uses

Units: EJ/yr



In 2023, 27% of the world's total final energy and nearly 50% of global electricity was consumed by buildings. A little under three-quarters (90 EJ) of this final energy demand was in residential buildings – houses and apartments – with the remaining quarter (34 EJ) attributable to commercial buildings – such as public workspaces, hotels, hospitals, and schools. Total CO_2 emissions from this sector amounted to 8.1 $GtCO_2$, about 24% of total energy-related CO_2 emissions last year, and two thirds of the building emissions come from power.

Energy efficiencies

As the global population increases towards the 9.5 billion mark in 2050 and living standards improve worldwide, we will see strong growth in energy services provided in the buildings sector – space cooling, space heating, water heating and cooking. While energy services will grow, the associated energy consumption (i.e. final energy demand) will not increase at the same speed thanks to energy-efficiency improvements driven by higher efficiency standards, a steady decline in the cost of new energy-efficient technologies, and improvements in the building stock (insulation). For example, heat pump technology, which uses a small amount of energy to transfer thermal heat from one area to another, can operate with an efficiency above 300% (the ratio between useful heating energy provided over electricity used). Figure 1.16 shows developments in useful and final energy demand for four different end uses in buildings. As mentioned above, there are starkly different growth rates in useful and final energy demand for all end uses. This is most visible

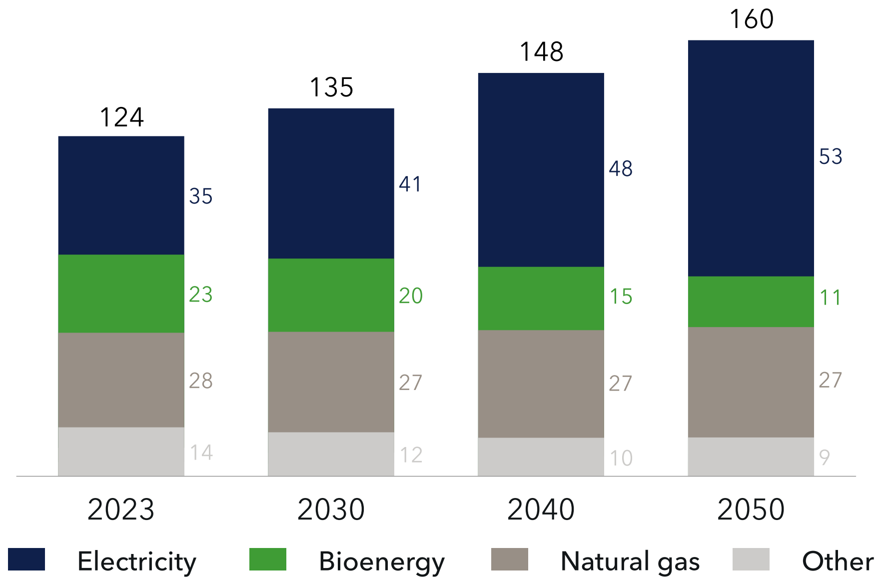
in space cooling, which is still expected to be the most important source of growth in energy demand from buildings over the next three decades which will see both rising average temperatures and increasing capacity to invest in cooling due to GDP per capita growth.

> The growth in electricity is most notable, growing from 35% of the mix in 2023 to 53% in 2050 with demand nearly doubling from 43 EJ in 2023 to 85 EJ in 2050.

FIGURE 1.17

Buildings energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2024)

Electrification of final energy demand

Developments in buildings final energy demand will vary by energy carrier (Figure 1.17). The growth in electricity is most notable, growing from 35% of the mix in 2023 to 53% in 2050 with demand nearly doubling from 43 EJ in 2023 to 86 EJ in 2050. This is due to the increasing demand for electric appliances in buildings, most notably heat pumps. Electricity's growth eats most into the share of biomass (principally, the traditional use of biomass is for cooking and heating), which declines from 23% of the mix in 2023 to 12% in 2050. Electricity takes a much smaller bite out of natural gas, which only declines from 28% to 25% over the same period. In the 2030s, we start to see hydrogen used for heating buildings, rising to a modest 1% share in the heating energy mix in 2050. This will initially be in the form of hydrogen blended into natural gas pipelines and later transition to some use of pure hydrogen. Hydrogen use in buildings will be rather limited due to it being expensive in comparison to increasingly cost-efficient heat pumps. For more on this topic, see DNV's *Hydrogen Forecast to 2050* (DNV, 2022a).

Appliances and lighting

In 2023, appliances and lighting used 28 EJ of energy, just over 20% of global buildings energy demand. Nearly all of this energy came from electricity. We expect this demand to rise to 46 EJ, with appliances and lighting's share of global buildings energy demand rising to 28%. There will be significant improvements in the energy efficiency of appliances and lighting and more intensive use of both. In our modelling, we take into account Jevon's Paradox, where efficiency gains are sometimes nullified by more consumption. We are also aware that as lighting and appliance use becomes more automated, for example through AI-enabled and automatically activated demand-response, efficiencies will accrue rapidly at the system level.

This year we have also dedicated more work to measuring the effect AI will have on energy demand from data centres, which falls under appliances and lighting. The growth in AI-linked energy demand will be tempered again by efficiency gains, but to what degree is still subject to debate. For more on AI and data centre energy usage, see our fact box at the end of this chapter.

Building Stock

'Floor area' is one of the most important drivers of energy demand in buildings. Energy consumption in key end uses such as space heating and cooling scale closely with floor area, as do associated energy efficiency improvements. In 2023, the global floor area of both residential and commercial buildings was around 262,000 km^2, about the size of New Zealand, split 85:15 in favour of residential. We expect the residential floor area to grow 46% by 2050 to reach 322,000 km^2 and commercial floor area will more than double to reach 84,000 km^2 in 2050. This will result in an 80:20 split of combined residential/commercial floor area.

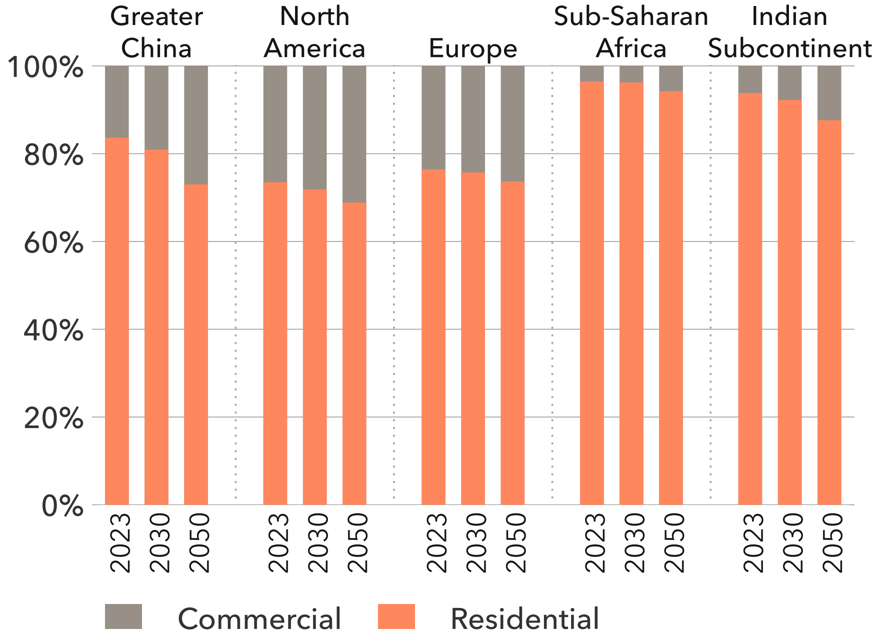
We expect the share of commercial buildings to grow in five of our target regions as GDP growth outpaces population growth (Figure 1.18). This is most visible in fast-growing regions such as Greater China and the Indian Subcontinent where GDP will grow much faster than population.

By 2050, Greater China's total floor area of buildings will be about 102,000 km^2, the largest by far of all our 10 regions, and roughly equivalent to the current (2023) floor area across the four other regions shown in Figure 1.18. It is perhaps not surprising then that buildings in Greater China will continue to consume nearly one-fifth of global buildings energy use. Improvements in energy efficiency and insulation will be key to tempering China's buildings energy use. For more insight into buildings and other topics in China, see DNV's *Energy Transition Outlook China* (DNV, 2024a).

FIGURE 1.18

Commercial and residential buildings – shares of total floor area

Units: Percentages



Space Cooling

In 2023, space cooling accounted for only 7% of the buildings sector energy demand. By 2050 this will have risen to 17%, split 75:25 between residential and commercial buildings. In absolute terms, energy demand for space cooling will similarly grow from 8.2 EJ a year in 2023 to 27.6 EJ a year in 2050. North America presently accounts for around 40% of global electricity demand for cooling. However, in 2050 about 30% of cooling demand will be from Greater China and only 13% from North America. Europe's electricity consumption for cooling will nearly double between 2023 and 2050.

The growth of demand for space cooling is due to three connected factors: a growth in floor area requires more cooling, increasing standards of living mean more people can afford cooling technology, and climate change causing an increase in cooling degree days (CDD – the cumulative positive difference between daily average outdoor temperature and reference indoor temperature of 21.1°C). Efficiency gains in insulation and cooling technology will play a large role dampening what could, *ceteris paribus*, be a runaway energy demand for space cooling.

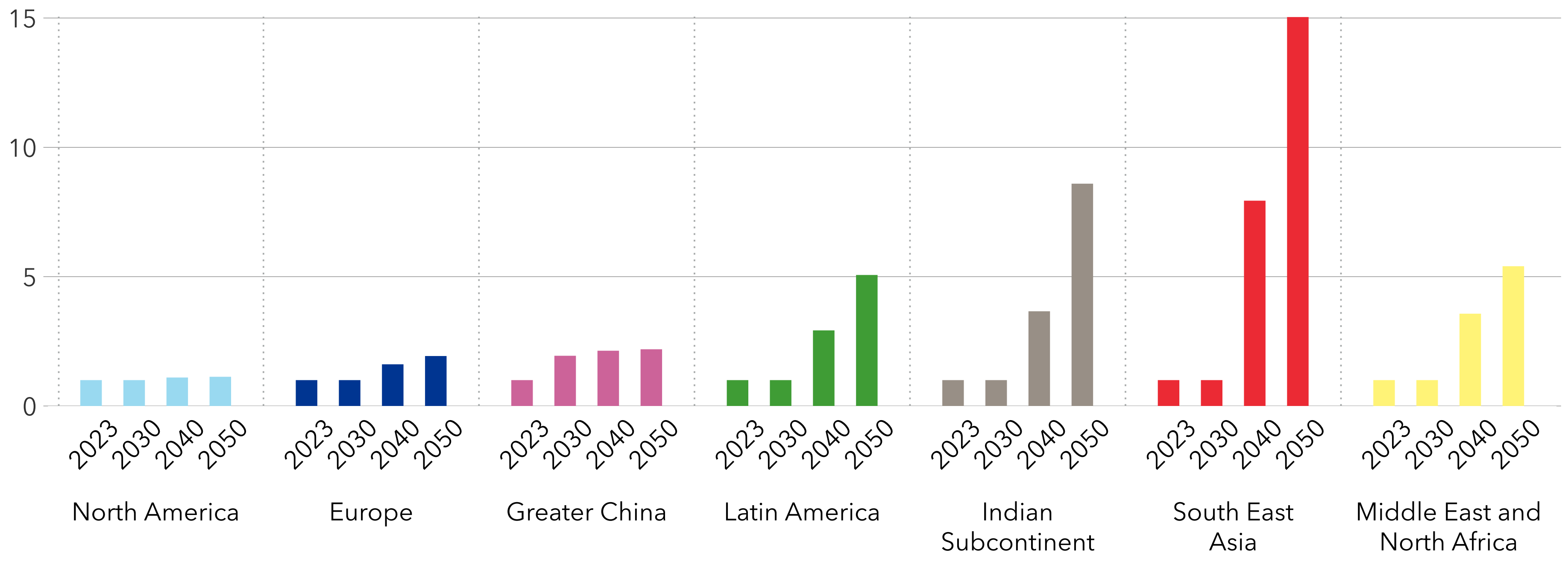
Heat-related weather events driven by anthropogenic emissions are becoming more frequent and space cooling is becoming critical for adaptation. Starting in the tropical and subtropical regions, living and most indoor work spaces in a progressively larger portion of the world will become unbearable without space cooling. This will particularly impact the infirm, elderly, and children (Vecellio et al., 2023). This distressing reality has profound climate-justice dimensions: the countries and regions least responsible for this warming are going to be most affected by it (Sharples, 2023).

Among our ETO regions, those with the highest future economic growth – such as the Indian Subcontinent, Latin America, South East Asia, and the Middle East and North Africa – are also most vulnerable to heat-related climate events and will demand the most cooling (Figure 1.19). These regions currently have CDD above 1000°C-days per year and this is only expected to increase. However, these regions will have unequal access to cooling due to income disparities. The region with the highest CDD in 2050, the Indian Subcontinent, will have a quarter of the world's population by then but will only consume about 13% of the world's cooling energy demand due to this region having a lower GDP per capita than some other high CDD regions. Indeed, the Indian Subcontinent is subject to a vicious cycle: extreme heat is already affecting worker productivity – a trend that will deepen – which, in turn, affects factory margins and reduces the ability of firms to pay for modern air-cooling systems (and wage stagnation likewise reduces the ability of workers to install air conditioning in their homes).

FIGURE 1.19

Cooling energy demand compared across selected regions

Units: Index: 2023 = 1



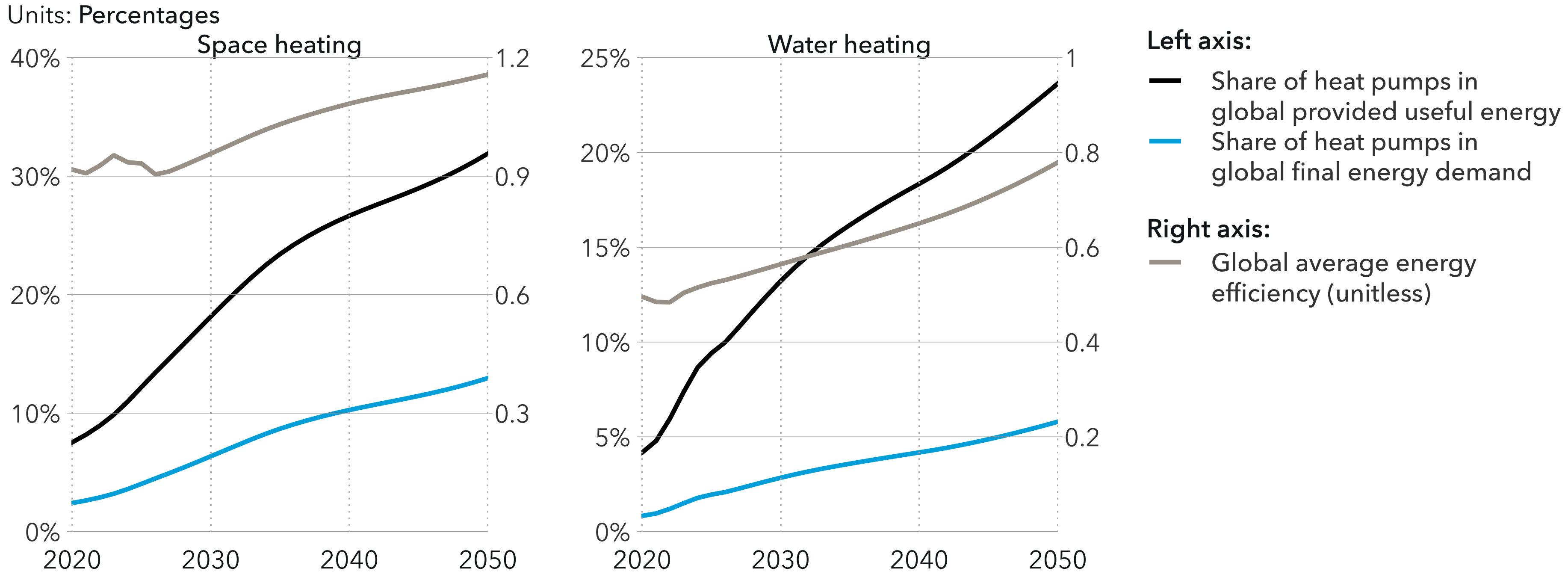
Space and Water Heating

Space and water heating accounted for 30% and 19%, respectively, of the buildings sector's total energy consumption in 2023, at 37 EJ and 23 EJ. Space heating will drop to 33 EJ in 2050 thanks to efficiency gains, while water heating remains the same. With an increase in population and greater floor area, demand for space heating will continue to grow, rising 9% in terms of useful heat demand energy (energy that is used for its specific purpose after all conversion losses have been accounted for) by 2050. Improvements in insulation, and fewer heating degree-days (a measure of how cold the temperature is on a given day or during a period of days) due to climate change will help reduce the rate of this growth.

GDP per capita is the main driver of demand per person for water heating in residential buildings. The water-heating demand of commercial buildings – about 28% of total final energy used for water heating – is instead driven primarily by floor area. Globally, demand for hot water will rise around 50% from 12 EJ of useful heat in 2023 to 18 EJ in 2050 due to increased availability of water heating technology in lower income countries. Today, in these countries, water is heated as required for basic needs using inefficient methods. However, by 2050 these regions will use hot water tanks similarly to higher-income regions: continuously to serve multiple needs, from daily showers to washing dishes.

FIGURE 1.20

Share of heat pumps and overall efficiency in space and water heating



Average efficiency of heating equipment is defined as the ratio of useful energy provided to final energy demand. This efficiency varies widely between technologies, from less than 10% for traditional open wood-burning to more than 300% for heat pumps which extract more energy in the form of heat from the air or earth than the energy they consume in the form of electricity.

By 2050, heat pumps will provide 32% of total useful energy for space heating (12.2 EJ) and 24% for water heating (4.2 EJ), while using only 13% and 6% of final energy, respectively (Figure 1.20). Thanks mainly to the expected transition from less efficient technologies – such as gas or biomass boilers to heat pumps for space and water heating – and gradual efficiency improvements in technologies, we see average efficiency rising from 0.95 in 2023 to 1.16 in 2050 for space heating, and from 0.5 to 0.78 for water heating.

The largest challenges in heat pump uptake today are the costs of energy-efficiency retrofits and 'split incentives' in rental housing where the costs of retrofitting are typically borne by the landlord but the benefits are seen by the tenants. However, we see a reduction in cost increasing the uptake of heat pumps. This is helped by cost learning feedback loops where the cumulative installed capacity of the technology brings down production costs. Costs vary between regions, but with a global learning rate of 15% we expect to see a reduction in the levelized cost of heating by heat pumps in all regions by mid-century. This cost reduction averages around 24% and varies depending on region.

Heat pump adoption also varies by region. In Europe, around 3 million heat pump units were sold in 2023, increasing the total number of heat pumps installed in the region to 20 million (EHPA, 2024). At present, China is leading the world in new sales of heat pumps – along with patenting, manufacturing and installation – with over 12 million air sourced heat pumps installed today (Rudgard, 2022). In some local markets, like Norway, where cheaper electricity prices reduce operating costs and long winters ensure a higher return on investment, heat pumps constitute most of the market even though cold temperatures mean a lower seasonal coefficient of performance.

For water heating, the move away from traditional biomass stoves is another big driver of efficiency improvements. Increased energy access will reduce

the final energy represented by traditional biomass for water heating from 38% today to 23% by 2050, resulting in savings of 3 EJ by 2050 (Figure 1.21). As a result of these developments, final energy demand for water heating will remain stable in the range of 23 to 24 EJ/yr from 2023 to 2050.

Final energy demand from space heating will fall from 37 EJ to 33 EJ over the same period due to further implementation of insulation and retrofitting measures and the use of more efficient electric heat pumps. In terms of the energy mix in space heating, we see electricity rising to a share of 25% of the mix in 2050, once again driven by electric heat pumps. In water heating in addition to the marked reduction in bioenergy, there are slight increases in the shares of electricity and natural gas, notably the latter.

Cooking

Cooking is an often-overlooked component of energy demand in buildings today, despite accounting for almost a quarter of building energy demand and 6.2% of final energy demand. We expect cooking energy demand to grow 5% from 28.2 EJ in 2023 to 30.2 EJ in 2050. The switch to more efficient cooking technologies will prevent a steeper growth in energy demand.

There are large regional variations in cooking technology and fuels. We estimate that in 2023, 47% of cooking energy demand was met by traditional biomass stoves burning fuels such as animal waste, charcoal, and wood. The majority of the people who use biomass stoves live in Sub-Saharan Africa and the Indian Subcontinent. By 2050, traditional biomass stoves will be replaced by electricity, gas stoves, and modern biomass stoves and traditional biomass will provide only 21% of final cooking energy demand. The choice of technology adopted regionally will vary depending on the availability and affordability of different energy carriers. The share of traditional biomass in Sub-Saharan Africa and the Indian Sub-continent will drop from 84% to 44% and 61% to 14% respectively.

The onus for cooking and sourcing the energy for it in regions such as Sub-Saharan Africa and the Indian Subcontinent traditionally falls on women and girls. Coupled with the aforementioned high prevalence of traditional biomass stoves, the IEA estimates that households without access to clean cooking fuels spend five hours per day collecting fuel and cooking. The time spent by women and girls on these tasks affects their opportunities for development, access to education, employment, and income. For this reason, cooking energy is an important driver of gender inequality and productivity loss. The transition to more efficient cooking technologies and fuels is key to solving this imbalance.

FIGURE 1.21

World space heating and water heating energy demand by energy carrier

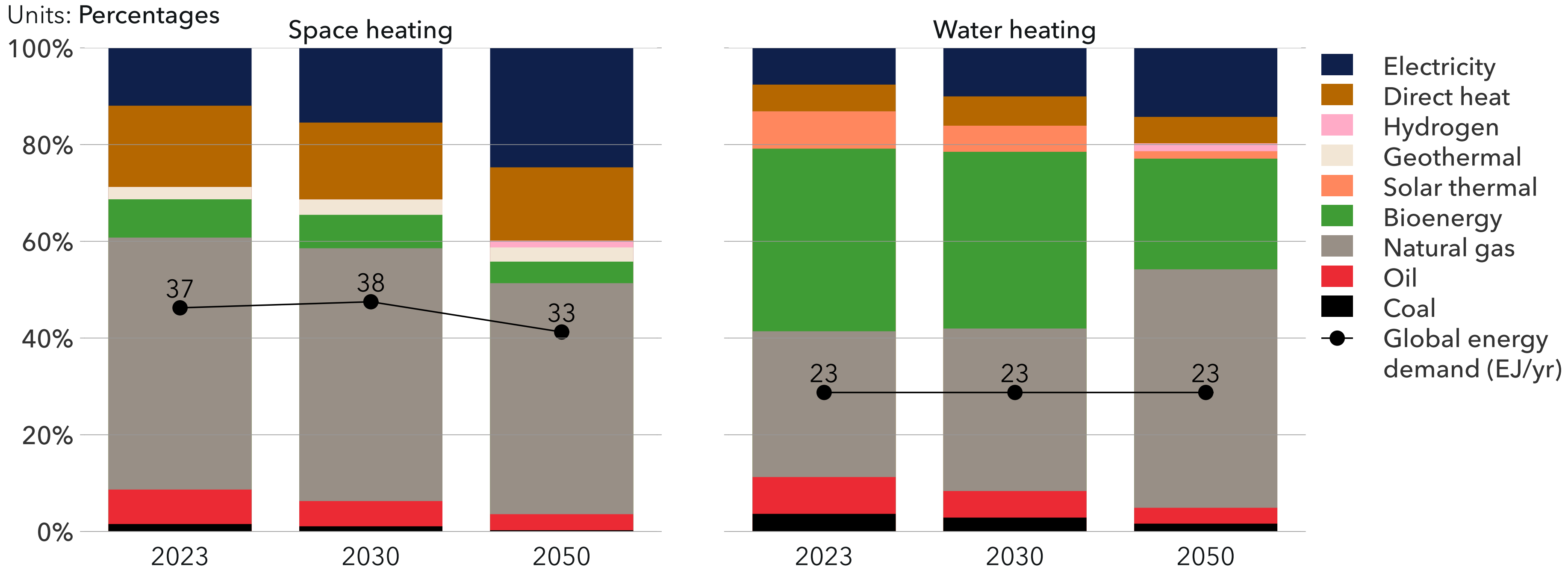
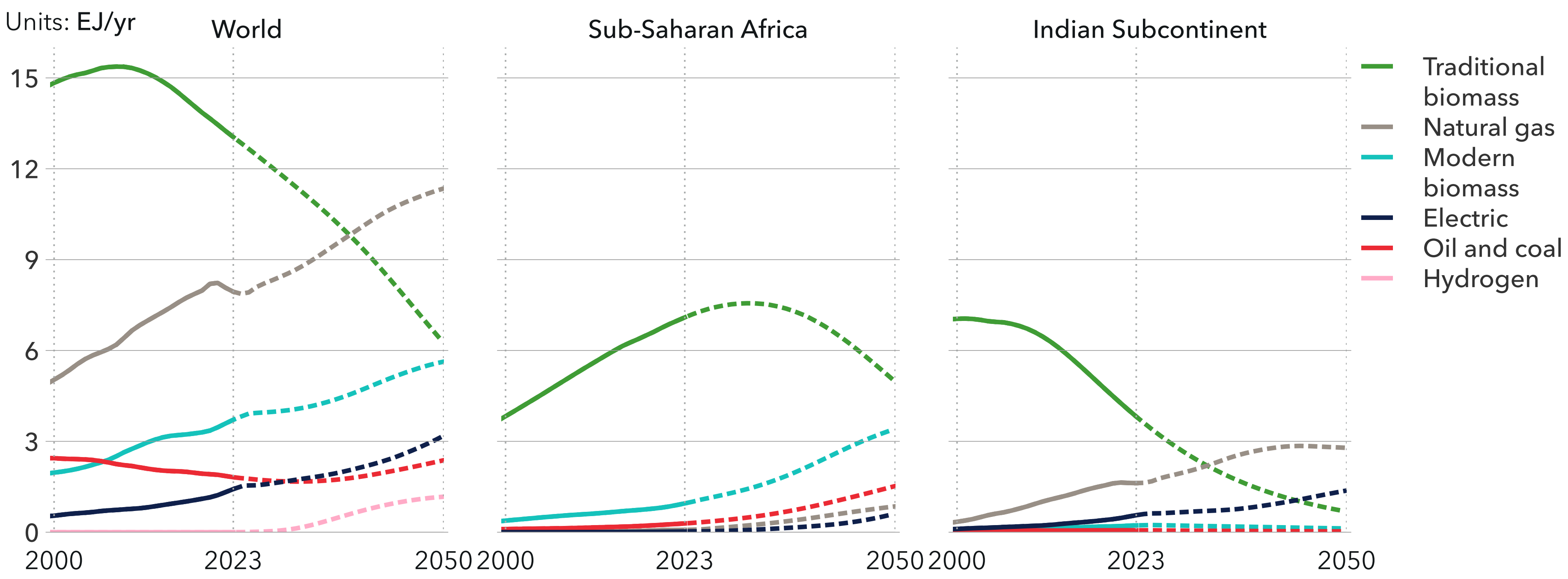
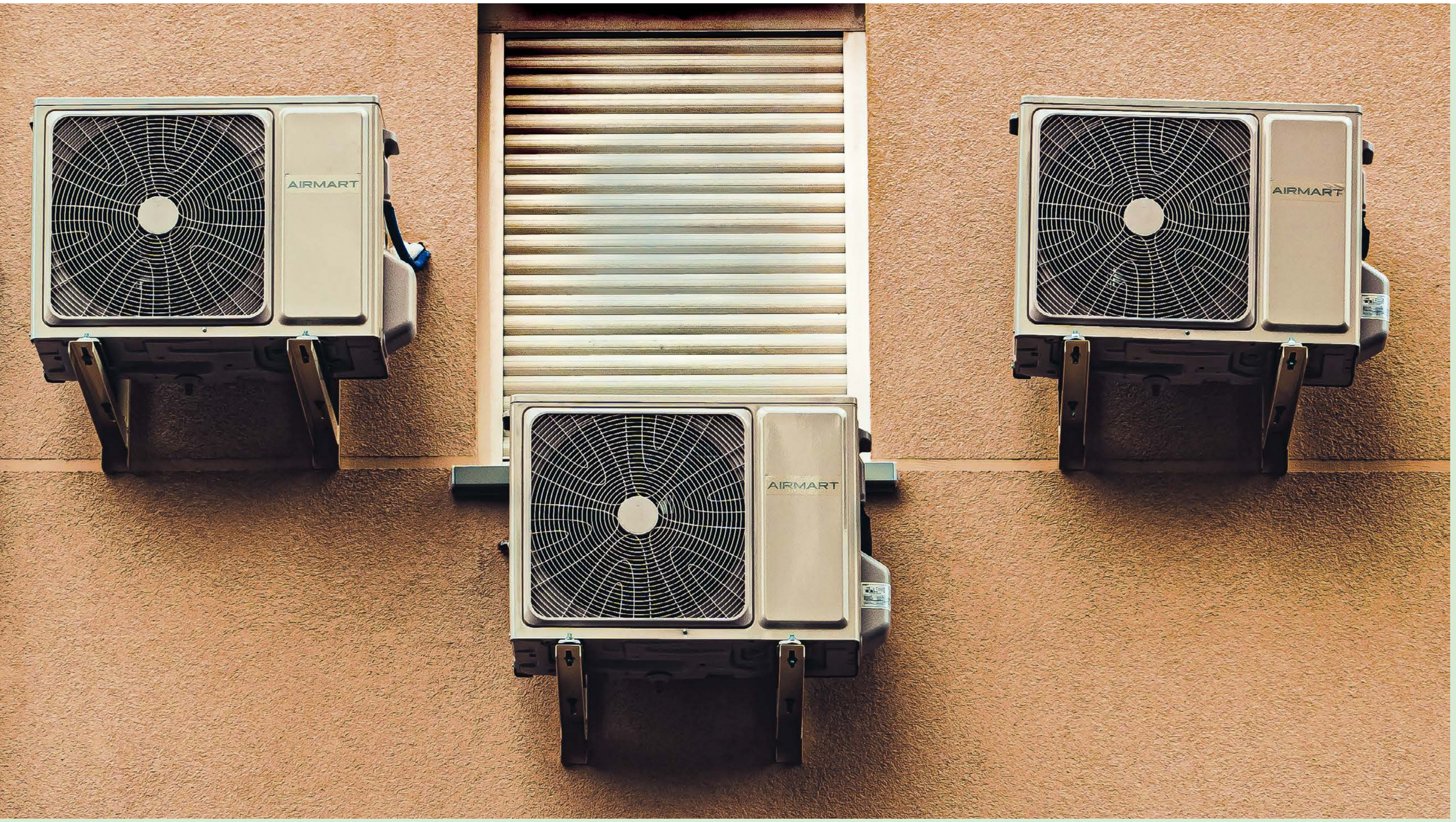


FIGURE 1.22

Cooking energy demand for selected regions and the world





Energy efficiency through heat pumps

Heat pumps are a critical tool in addressing climate change over the next decades. As the planet warms and extreme weather increases, heating and cooling buildings will become increasingly important, and in many cases indispensable. Because heat pumps are substantially more efficient than other systems, they decrease the total energy demand for heating and cooling. In addition, being entirely electricity-based means that they can replace traditional fossil fuel- or biofuel-based systems and reduce GHG emissions.

Why heat pumps?

A heat pump uses electricity to transfer heat from a cold area to a warm one, or vice versa. The most common heat pumps used in residential buildings are air source heat pumps, which can absorb heat from the air outside a building and transfer it inside. There are also air to water heat pumps which work similarly, moving heat from the air outside a building to water inside a building which can distribute the heat using radiators or underfloor heating. As heat pumps use electricity to move heat rather than generate it, they are much more efficient than other heating technologies when measured by their co-efficient of performance (CoP). A typical CoP for a heat pump is higher than three, meaning that for every 1kW of electricity used, over 3 kW of heat can be produced. The equivalent hydrogen boiler would only have a CoP of about one.

For this reason, heat pumps will be key to decarbonizing the buildings sector and improving energy efficiency. We foresee an uptake of heat pumps towards 2050 that is highly regional, with high-income regions with winter heating needs, like North America and Europe, leading uptake first, followed by middle-income China. In warmer parts of the world where heat pumps can also be used to meet some space cooling needs, such as in OECD Pacific, we also see some uptake towards 2050.

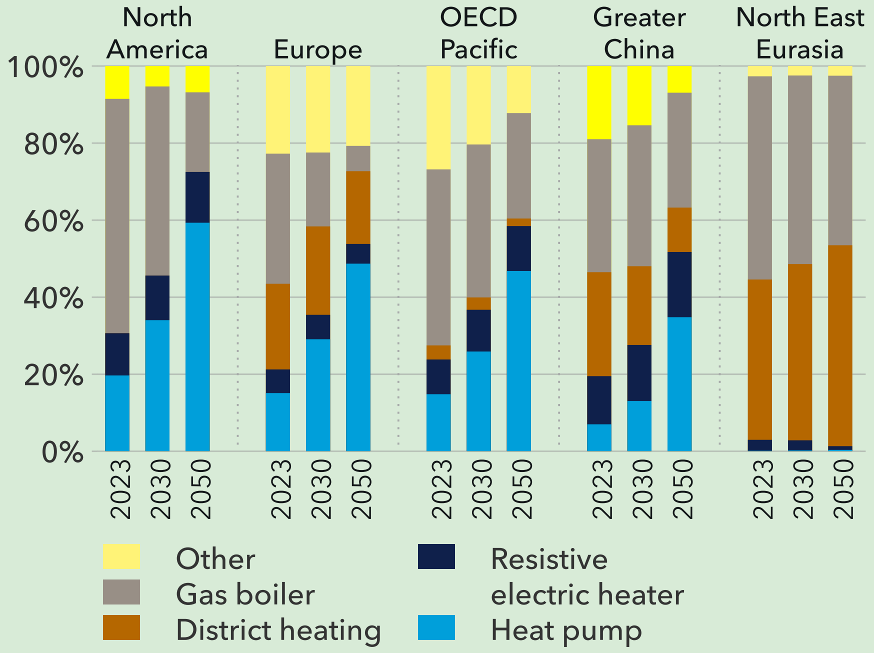
Heat pump adoption

Today, Europe's space heating needs are dominated by natural gas boilers at 34% with heat pumps making up only 15% of the mix, involving around 31 million homes. By 2050 however, heat pumps will have seen significant growth and will make up nearly 50% of the mix (122 million homes). In North America the story is similar, with natural gas dominating today at 60% of the mix (86 million homes) but declining towards 2050 when heat pumps will make up 60% of the mix

FIGURE 1.23

Regional shares of selected space heating technologies

Units: Percentage of households



of heating technologies, heating 113 million homes. China is leading the world in new sales of heat pumps, along with patenting and manufacturing. It will see heat pumps grow to make up 35% of the technology mix to serve 311 million homes, mostly in the south of the country where heat pumps are used both to heat residences in the winter and cool them in the summer.

The adoption of heat pumps will rely on several factors. The efficiency advantages of heat pumps are one, but potential consumers are also concerned about upfront and running costs, levels of disruption, and changes to their lifestyle.

The upfront costs of heat pumps are currently three to four times more than an equivalent gas boiler. Today, some governments are subsidizing the cost of heat pump installation through rebate programmes, such as the *Oil to Heat Pump Affordability Program* (OHPA) in Canada or the *Boiler Upgrade scheme* in the UK. However, not all homes are eligible and the financial support does not always cover the entire installation cost. In the future, we see the investment costs of heat pumps declining significantly to around half of today's levels, making adoption more affordable in the future.

There are two factors to consider in keeping running costs low: insulation and energy prices. For heat pumps to work most effectively, an energy performance certificate (EPC) rating of C or higher is needed. If a building has a rating lower than this it will need additional investment in insulation. With newer buildings having higher EPC ratings and continued retrofitting of older buildings, we see an increasing share of buildings being heat pump ready towards 2050. Electricity prices in comparison to competing energy carrier prices, notably natural gas prices, will also influence whether or not it is economically viable to run a heat pump. As the gap between lower gas prices and higher electricity prices shrinks, heat pumps will become a more attractive option.

To many people, heat pumps are a new and unfamiliar technology that will necessitate small changes in thinking and lifestyle. For example, consumers will need to be aware that, unlike gas boilers, it is more effective to leave heat pumps running all the time. In the very cold climates of inland North America, concerns linger that heat pumps will not be sufficient to heat houses when the temperature is below -20°C or during peak periods of electricity usage. While heat pumps do become less effective at lower temperatures, newer ones can operate to at least -20°C and possibly lower and it is possible to have gas heating as a backup. A buildout of the grid will allow for enough electricity capacity during peak periods.

Karman Industries' mass manufactured heat pump leveraging advanced technology from the aerospace and electric vehicle sectors. Image, courtesy Karman

1.3 MANUFACTURING

The manufacturing sector holds a dual role in the energy transition; while it is one of the hardest-to-abate sectors, it will also become a key enabler for low-carbon solutions.

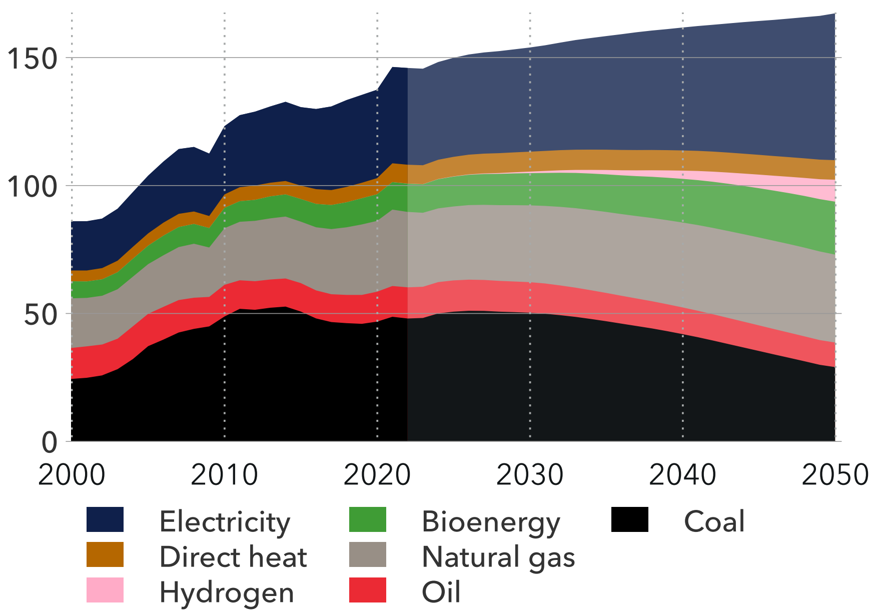
Unlike in power and transport where emissions already show a marked decline in the next five years, emissions in the manufacturing sector will continue to increase in the next decade before falling. Even then, manufacturing emissions do not fall as steeply as the other two sectors. In 2050, almost 40% of global energy-related and process emissions will come from the manufacturing sector.

There are three main reasons for the emissions inertia in manufacturing. The first reason is that current and future manufacturing energy demand is dominated by a few energy-intensive heavy industries (e.g. steel, petrochemical, cement). The overwhelming majority of new installations in these industries still rely on fossil fuel-based technologies. As these plants are capital-intensive, long-term investments, only moderate changes in the fuel mix will be implemented during our forecast period.

FIGURE 1.24

Manufacturing energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2024)

A second reason is the diversity, often plant specific, of technologies and processes related to location and access to the relevant infrastructure. There is no one-size-fits-all decarbonization solution and new technologies are still being developed. There are very few challenges that manufacturers share in common, but high heat requirements where electrification is challenging is an important one.

A third reason is that the consumption of manufactured products will automatically increase with the near doubling of global GDP and the 1.6 billion increase in population during our forecast period. The associated ramp up in manufacturing output will outstrip efficiency gains and energy demand will increase by 15% by 2050.

While manufacturing remains a significant emitter, the sector will also be an enabler of large-scale clean tech like hydrogen or CCS. CCS will capture 270 $MtCO_2/yr$ (5% of the sector emissions) by 2050. Industrial heat pumps will also supply an increasing share of low- and medium-heat needs.

The complex future energy mix in manufacturing is shown in Figure 1.24. 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 two thirds of global demand at the end of our forecast period and making up 5% of the fuel mix.

These global trends are a composite of different sub-sectoral and regional dynamics (Figure 1.25). Iron and steel manufacturing has the highest global energy demand and will retain its position due to a stable demand for steel during our forecast period. Manufacturing of goods, driven by increasing GDP per capita in all regions, has the highest increase at 39%.

As detailed in in the sidebar 'Manufacturing on the move' at the end of this section, the next decades will play out very differently across regions. 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. China has a remarkable decrease in manufacturing (32%), whereas OECD regions are stable. Today's main energy carrier, coal, will be driven by persistent use in Greater China and the Indian Subcontinent. Together, these two regions will still represent two-thirds of demand by mid-century.

Economics of the transition: Balancing decarbonization targets and competitivity

Understanding the energy transition in the manufacturing sector requires an understanding of both the globalized nature of the sector and the different regional contexts.

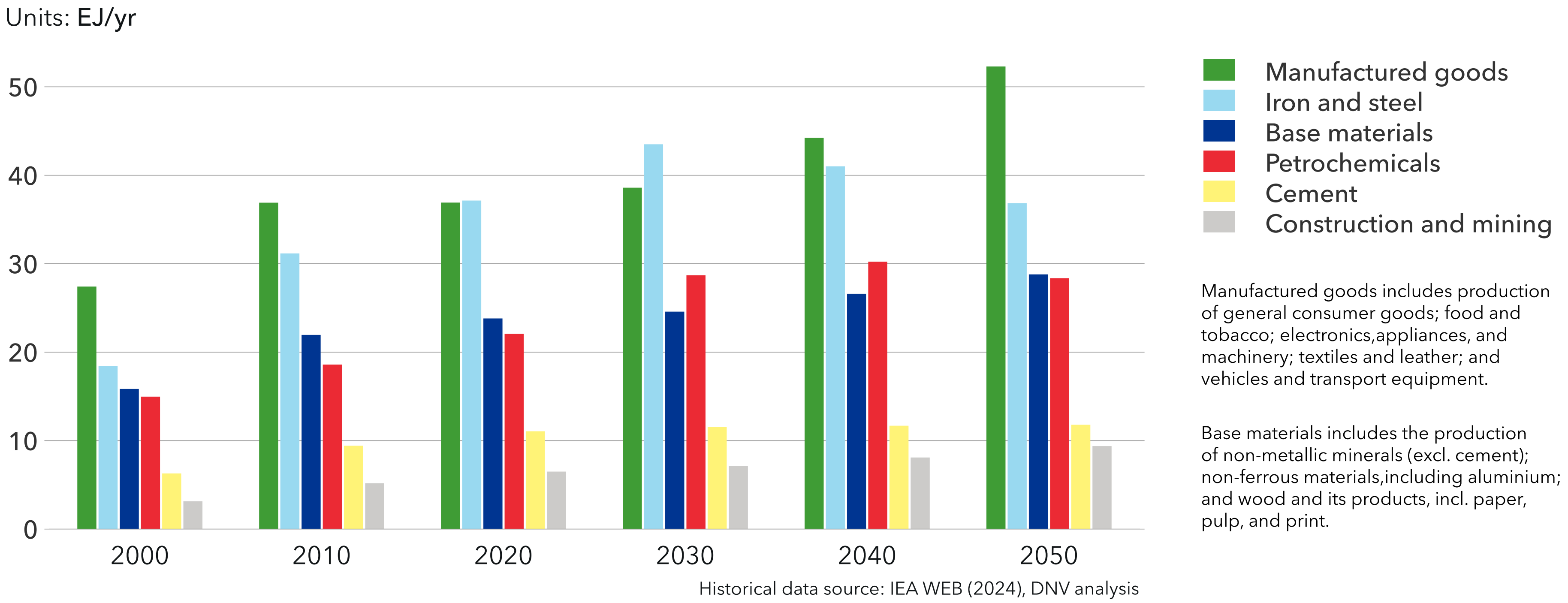
In addition to the complexity of evolving energy-related parameters (Figure 1.26), manufacturers face difficult make-or-buy decisions given the recent growth in local content requirements. Whether complying with these requirements or facing the full effect of global competition, there is limited leeway for risk taking.

Long-term predictability is important to reassure investors and secure investments, especially for policies addressing climate change and GHG emissions (PwC, 2022). *The Inflation Reduction Act* in the US, the *Net-Zero Industrial Act* in Europe, and the *14th Five-year plan* in China are recent examples of policies shaping the future of industries globally. Carbon price and related measures such as carbon border adjustment mechanisms are also powerful tools that will continue to shape the transition in regions like Europe.

In addition to the regulations from regional, national, and local authorities, manufacturers are seeing ever

FIGURE 1.25

World manufacturing energy demand by subsector



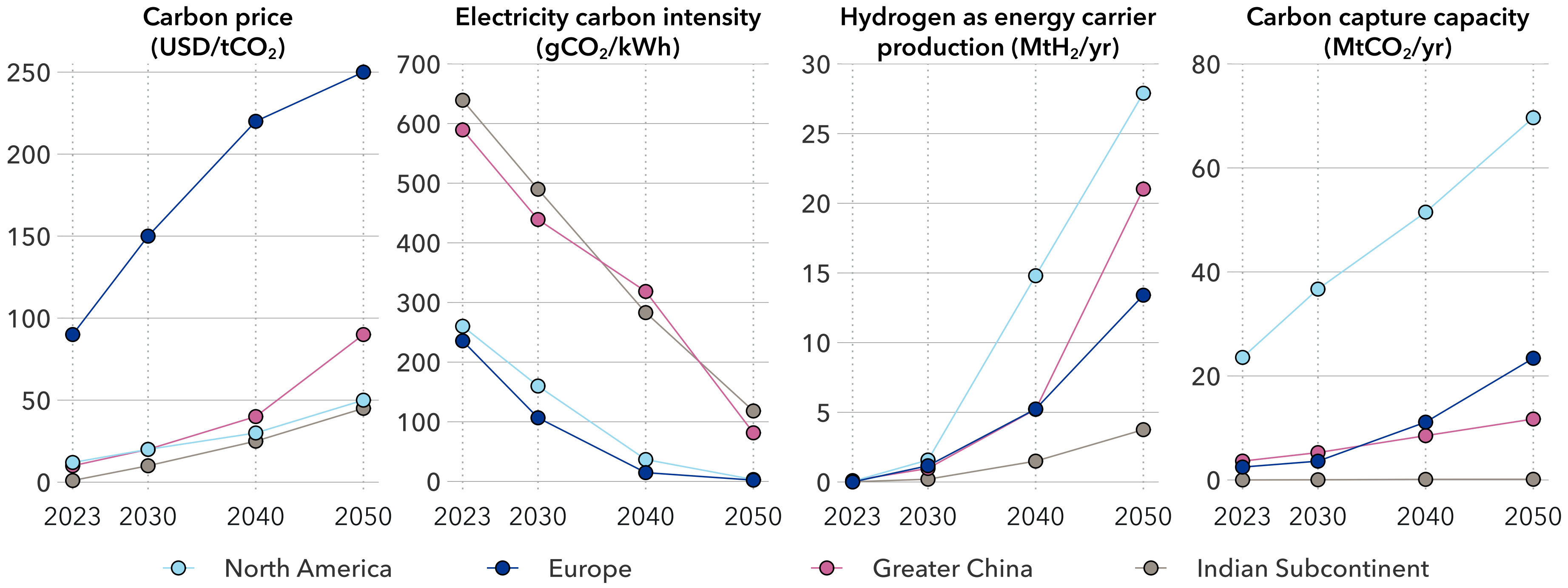
Manufactured goods includes production of general consumer goods; food and tobacco; electronics,appliances, and machinery; textiles and leather; and vehicles and transport equipment.

Base materials includes the production of non-metallic minerals (excl. cement); non-ferrous materials,including aluminium; and wood and its products, incl. paper, pulp, and print.

Historical data source: IEA WEB (2024), DNV analysis

FIGURE 1.26

Key policy and market parameters for the manufacturing sector in selected regions



stronger market drivers for decarbonization from their downstream supply chain and the end-users of their products. Early adopters are pushing for certified decarbonized inputs like low-carbon cement or steel. Their willingness to pay a premium helps build the market and develop technologies that would not otherwise be competitive (McKinsey, 2022).

All of this is leading an increasing number of manufacturers to improve control of supply chain reliability and transparency. In parallel, many industry actors will have an ambition to deliver on science-based targets, which also increases dialogue and cooperation with suppliers to reduce footprint (SBTI, 2023).

Another two important parameters are the current state of the manufacturing infrastructure and the expected future demand. Manufacturing investments usually entail a long time horizon, locking in location, technology, and emissions. This makes the sector traditionally risk averse, which is slowing down the uptake pace of capital-intensive decarbonized alternatives.

Additionally, in the short- and medium-terms, new technologies such as hydrogen-based processes or CCS projects will rely on fragile supply chains with little flexibility in case of a disruption. Transitioning from being buyers in well-established and resilient commodity markets to becoming more actively involved in securing their supply chains is a paradigm shift for first movers. This is illustrated by manufacturers increasingly investing in renewable power to ensure low-carbon electricity supply (World Steel, 2022). Other strategies such as sector coupling, heat-as-a-service, and flexibility services are also emerging to de-risk investments (WBCSD, 2022).

Gauging the right level of investment

A 'do nothing' approach to decarbonization is becoming increasingly untenable. The question then is how far a manufacturer should go in investing in decarbonization options.

Energy efficiency measures on existing installations are a common option to increase profitability because of lower CAPEX and shorter downtimes and ROI. These investments may also be needed to keep pace with new installations which are usually built with energy-efficient technologies, regardless of local climate policies. For example, the booming nascent Indian cement industry is among the most energy-efficient in the world (CEEW, 2023).

Climate policies commonly include funding for energy efficiency measures that lower the threshold for investments. In Europe for instance, an EU directive requires the implementation of energy management systems (EU, 2020), while at a country level, Germany tightened regulations to increase energy efficiency improvements (Alkousaa et al., 2023).

Other low-CAPEX options include fuel shifts that do not impact the core of a production plant. An example of this is a petrochemical plant shifting from coal to gas or bioenergy in steam production. For downstream companies that cannot control their supply chains, carbon credits or offsets are also an attractive but controversial zero-investment option (Carbon Brief, 2023).

Investing in deeper decarbonization (e.g. CCS, hydrogen) is a riskier decision and generally entails a higher cost of capital reflecting the risk. These investments invariably come with a higher price tag than the well-established technologies and are prone to delay and cost overrun (IISD, 2023). That's why even if projects could be competitive on paper, the actual pipeline only consists of a limited number of projects.

> A 'do nothing' approach to decarbonization is becoming increasingly untenable. The question then is how far a manufacturer should go in investing in decarbonization options.

A plethora of technological solutions

On top of a competitive market, one additional layer of complexity is that the various manufacturing subsectors will approach the coming decades with many energy and decarbonization options ranging from status quo to investment-intensive processes (Figure 1.27). The choices between these options will be made according to technological availability and cost, local regulations, and opportunities.

Energy efficiency is a must

Improving energy efficiency (Section 1.5) is usually the lowest hanging-fruit for both emissions and cost savings in the manufacturing sector. The history of heavy industries, for which fuel supply is one of the main expenses, has been shaped by the introduction of more efficient technologies. The transition from wet to dry kilns for cement production, or from open hearth furnace to basic oxygen furnace for steel production, has saved considerable amount of energy and accelerated the phase-out of the least efficient plants.

Better energy efficiency can also be achieved with the use of different input materials such as recycled materials in metals manufacturing. Steel production from scrap in electric arc furnaces uses one tenth of the energy than of the coal-intensive blast furnace route (IEA, 2020). As a result, this is a very competitive route and 23% of steel production currently comes from scrap. We forecast this share to almost double by 2050. Similarly, 75% of all aluminium ever produced is still in use thanks to recycling (International Aluminium, 2021). However, recycling is limited by the waste flow, and as demand grows virgin products are also needed. Other sectors with higher recycling costs are more driven by regulation such as those outlined in the UN *Global Plastics Treaty* due to be signed in 2024.

Electrification where possible

While total manufacturing energy demand is projected to increase by 20% to 2050, manufacturing electricity demand will increase around 50% over the same period.

The challenge for electrification lies in supplying industrial heat, which currently represents about two-thirds of manufacturing energy demand and is largely supplied by fossil fuels. For low-temperature processes, industrial heat pumps with efficiencies above 100% are competitive in regions where electricity to gas price ratios are lowest (DNV, 2023).

Electrification of high-temperature demand is more challenging. Several technologies are competing but none stand out at the moment. High-temperature heat pump applications (IEA, 2024b) and thermal storage (Harrabin, 2024) are gaining momentum but are currently only available as pilot- and small-scale industrial demonstrations. SMRs could provide both heat and power to energy-hungry plants, but no FID has been decided yet. We forecast a limited uptake for these technologies by 2050 because of their low levels of maturity.

There may be standout exceptions, where, for example, advanced thermal storage systems are linked directly to dedicated renewable electricity (and not straining distribution grids), but they are likely to be limited in number. In most regions, there is already a fierce competition between end-users to secure access to a large supply of low-carbon electricity and access to the grid.

Hydrogen and CCS on the high end

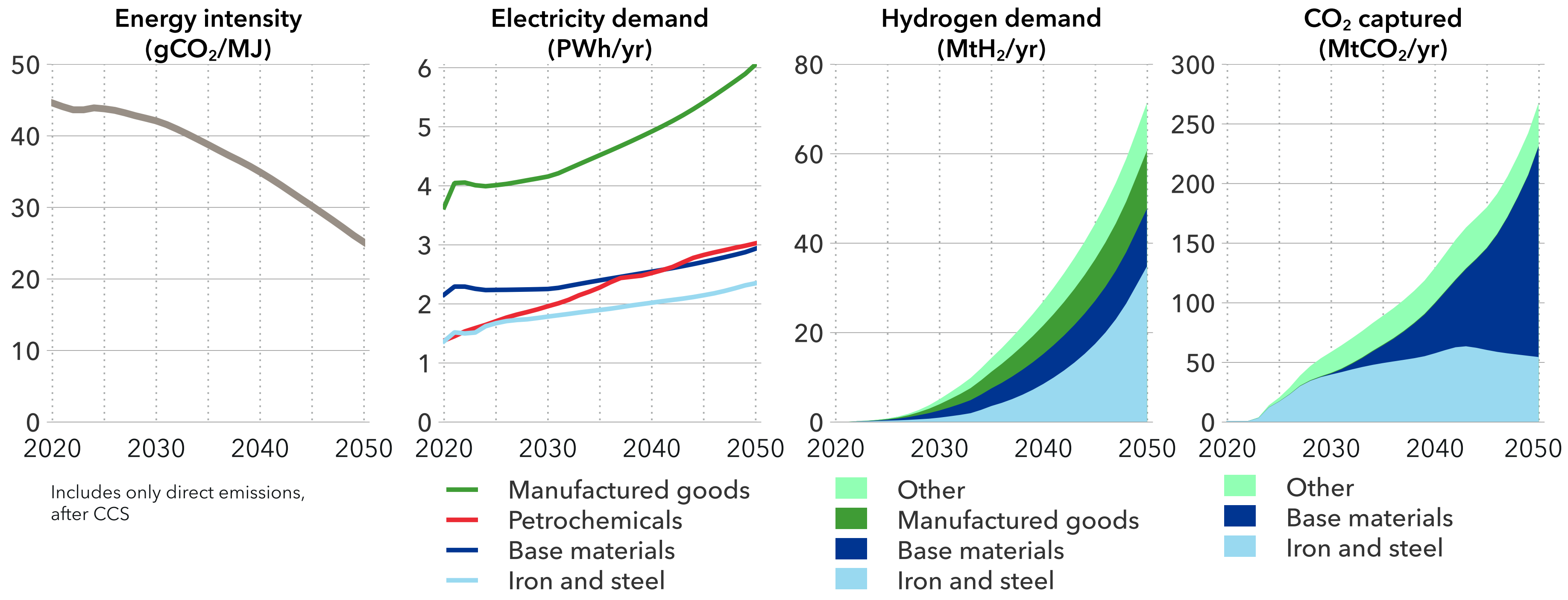
Where electrification is impractical or impossible, we forecast two main decarbonization options: hydrogen and carbon capture. These are CAPEX-intensive and riskier solutions, and manufacturers opting for these technologies will only be competitive under conditions of sufficient carbon price, enabling regulation, strong support, and dedicated markets.

The manufacturing sector will represent more than two-thirds of hydrogen demand as an energy carrier over the forecast period, and the molecule will cover 5% of the sectoral energy demand by 2050. Within the manufacturing sector, iron and steel production will be the main user of hydrogen, both as a reducing agent in the hydrogen direct reduced iron route and as a heat source in blast and electric arc furnaces.

Carbon capture will be used to retrofit fossil fuel-based processes. It is an attractive solution for plants that are located close to CO_2 transport and storage infrastructure, preferably in industrial clusters to enable economies of scale. Blast furnaces, cement plants with their inevitable process emissions, will drive CCS uptake in manufacturing. A fifth of CO_2 captured in 2050 will come from the manufacturing sector.

FIGURE 1.27

Uptake of decarbonization solutions in the manufacturing sector

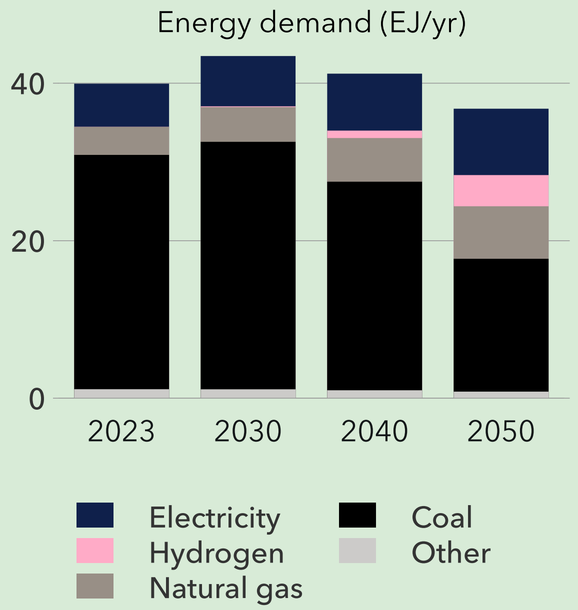


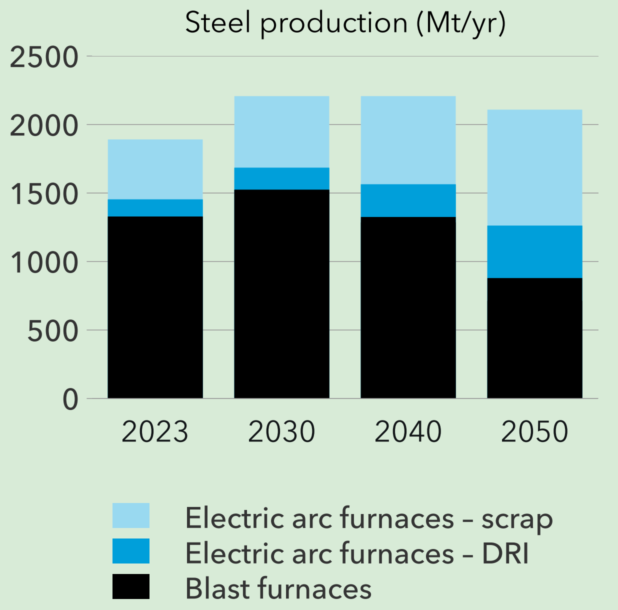
Includes only direct emissions, after CCS

Iron and steel

27% of manufacturing energy demand in 2023

Steel production has doubled in the past two decades, due mainly to infrastructure and industrial developments in China. Steelmaking is showing signs of slowing in China, but other regions, like the Indian Subcontinent, are still developing their infrastructure. We forecast production to grow just 15% by the mid-2030s and then plateau. The more efficient electric arc furnace (EAF) method's share in global steel production will progressively increase from 29% in 2023 to 58% in 2050. This will be driven by an increasing processing of scrap steel, the primary feedstock for EAF. There will also be strong growth in direct reduced iron (DRI), a critical feedstock for EAF steel that uses coal, natural gas, or hydrogen and requires both lower temperatures than traditional blast furnace-basic oxygen furnace ironmaking and little to no coke. Consequently, energy demand for steelmaking will decline from the mid-2030s. Coal use will progressively decrease but will still meet about half the subsector's energy demand by 2050 and steel will represent more than a quarter of global coal demand in 2050. A drive towards low-carbon steel through the DRI-EAF route will also increase the subsector's use of hydrogen for energy from practically zero today to 11% of its fuel mix by 2050.

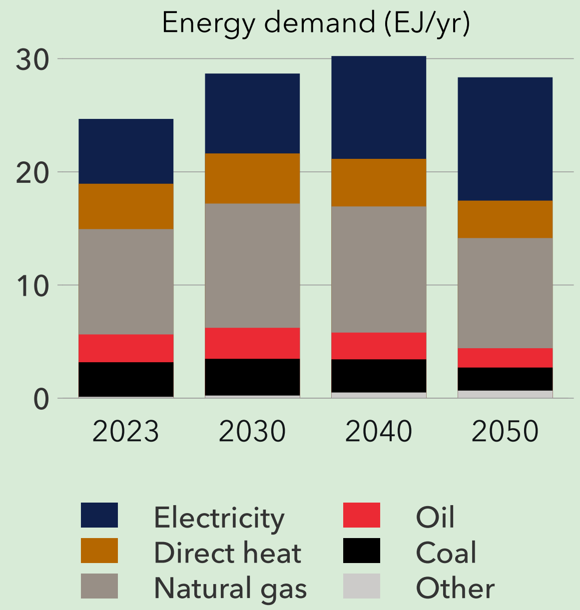


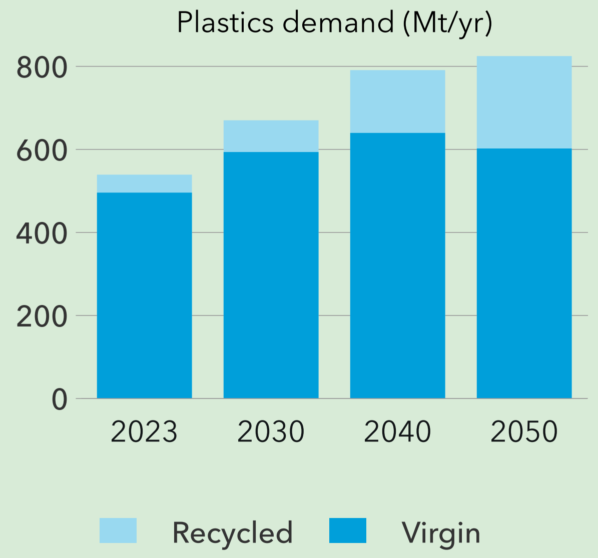


Petrochemicals

17% of manufacturing energy demand in 2023

We predict the subsector's energy demand to grow by about 20% between 2023 and the mid-2030s and then slowly decrease until 2050. The variation in energy demand is mostly attributed to the demand for virgin plastics. We expect this demand to initially continue increasing exponentially but become progressively attenuated by higher recycling rates in all regions (see Section 1.4 for more details). Energy and non-energy uses are mostly intertwined in today's industrial processes. Future processes like green ammonia production or electrified steam cracking will progressively decouple these two distinct uses in the subsector. However, long-life, multi-billion-dollar petrochemical sites operate on a fragile equilibrium. Heat recovery is well-developed, and excess heat or by-products from some processes often fuel others. Retrofitting options are consequently limited, as are potential energy-efficiency gains. This leads us to expect a slow transition in the energy mix, slow uptake of hydrogen for energy, and slow electrification.



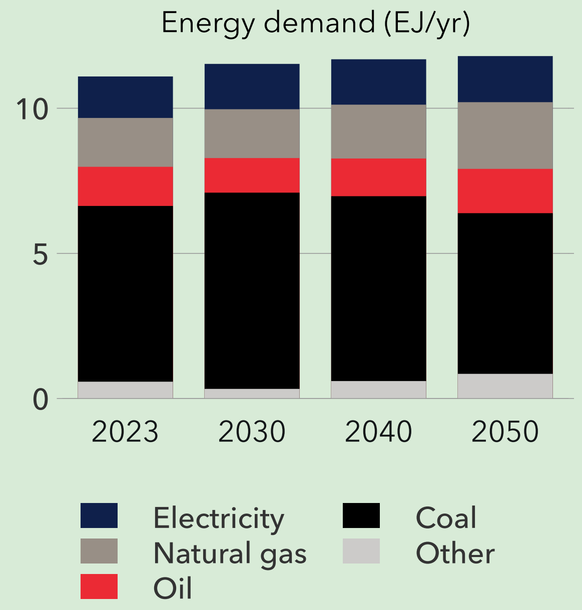


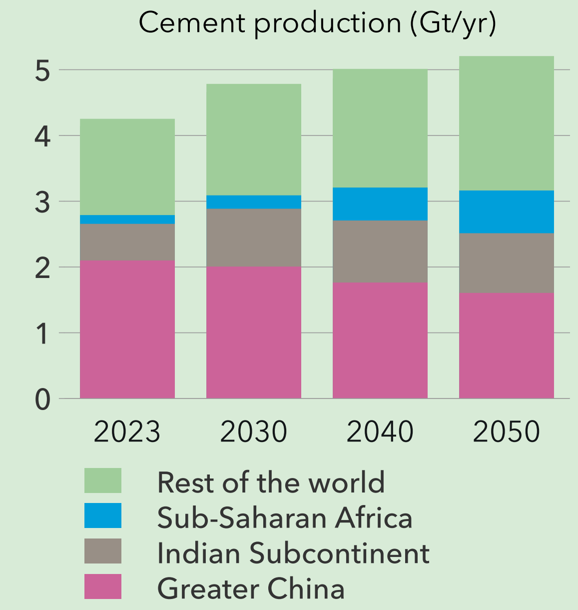
The sector includes the manufacture of plastics and other petrochemicals, incl. ammonia and methanol used as feedstock

Cement

8% of manufacturing energy demand in 2023

Cement production has more than doubled from 1.7 billion tonnes in 2000 to 4.1 billion tonnes in 2023. Half of global production currently sits in China. Like for steel, the slowing construction industry means decreasing production, especially given that cement is costly to export. The uncertain magnitude of the decline in China will have an outsized influence of future global demand. Our current forecast shows the growth in the Indian Subcontinent and Sub-Saharan Africa outpacing this decline and production steadily increasing to 5 billion tonnes in 2050. Hydrogen and electrification are expected to play limited roles due to high-temperature requirements and the necessity of abating the process emissions of cement regardless of the energy mix. On top of that, waste recovery (e.g. tyres, plastics) often creates a substantial source of income and a replacement for fossil fuels which can represent up to 100% of the fuel mix and easily compensate for high carbon price. Material efficiency, particularly lower clinker-to-cement ratios, will decrease energy demand. However, the fuel mix will remain highly carbon-intensive and decarbonization goals will have to be covered with carbon capture and storage.





Industry on the move

Harsh global competition is not a new concept in manufacturing. Famous examples include steel production after WWII and auto industry rivalry between the US, Europe, and Japan in the 1970s. However, the dominant position that China has built over the last two decades – on all steps of complex manufacturing supply chains, from base materials (steel, chemicals) to high-end products (batteries, solar PV) – is unprecedented. Other regions have hitherto generally seen this as a positive by lowering the costs of manufactured products, but global geopolitical developments are challenging this view.

China kicking off

As described in our recent report on China (DNV, 2024a), the dominant role of the country in global manufacturing did not happen by chance, but is rather the result of a long-term strategy, with state-owned and private companies both playing their roles. The government's annual economic growth targets rely on a production-intensive stimulus approach to achieve economic goals, and cleantech industries are key propellors of future growth.

The current strength of China is that, unlike the rest of the world, the country has built complete, almost independent supply chains. China is dominating current global capacity in some key sectors (Figure 1.28). Manufacturing was China's largest consumer of energy in 2022, accounting for over 50% of the country's final energy demand.

The growth in heavy industries in China was mainly aimed at satisfying local demand, and much of production was absorbed domestically. Now that the Chinese economy is slowing down, Chinese producers face an overcapacity issue, and many are exporting their products at very low prices, threatening industries all over the world. Warning about overinvestment by China in steel, EVs, and other goods, US Treasury Secretary, Janet Yellen, recently stated that, 'China is now simply too large for the rest of the world to absorb this enormous capacity' (Liu, 2024).

The world's reaction

Many OECD countries are now considering the situation a national economic security problem, and trade tariffs, anti-dumping regulations, and other protectionist measures are being baked into reindustrialization policies.

Siemens Energy together with joint venture partner Air Liquide opened a new electrolyser production facility in Berlin ©Siemens Energy.

The **US** is used to adopting drastic measures to protect its own industrial interests and will likely continue to do so. Trade tariffs on Chinese steel, solar PV panels, or more recently EVs, are examples of this behaviour. The *Inflation Reduction Act* (IRA) and the *Infrastructure Investment and Jobs Act* (IIJA) have additional protectionist measures, such as domestic content requirements, that will also restructure the current manufacturing capacity by making a clearer case for decarbonized energy. The recent refusal of the sale of US Steel to a Japanese company shows that protectionist measures not only target Chinese companies.

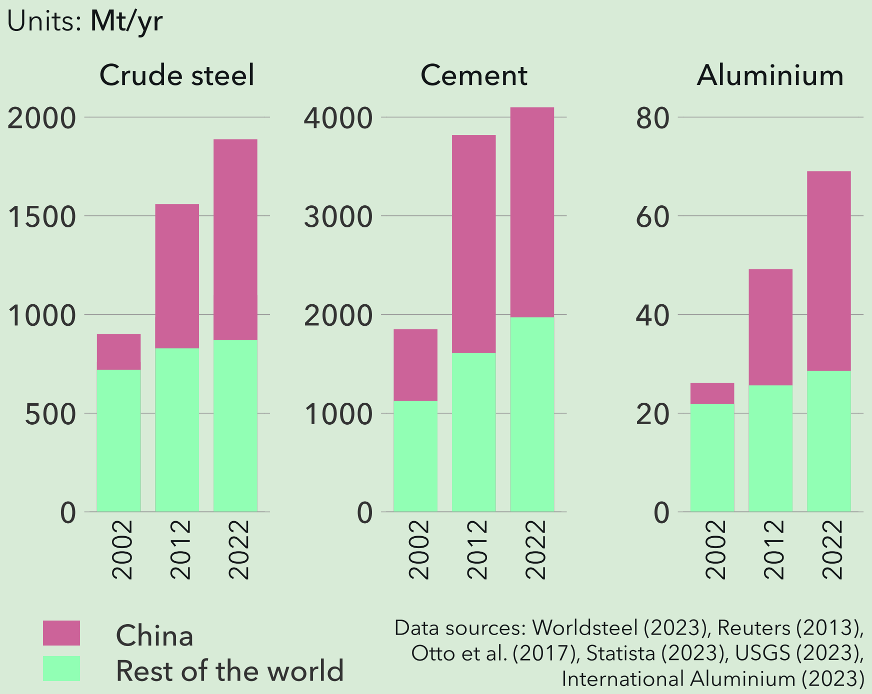
The **EU** is taking a less defensive stance towards Chinese competition. The EU is aiming at correcting the imbalance and is aspiring to regain domestic shares of production, through policies like the *Net Zero Industrial Act* and the *Critical Raw Materials Act*. Industry associations are concerned that protectionist measures will be put in place too late for some key industries like petrochemicals (CEFIC, 2024) or steel (Eurofer, 2024a). The implementation of the carbon border adjustment mechanism (CBAM) from 2026 also adds a lot of uncertainty as free allowances will be progressively phased-out and industries will face an increasing carbon price, threatening their competitiveness and exports. The transfer of numerous projects from Europe to US following the IRA is also a sign that the competition is not one-sided.

China's neighbours in the OECD Pacific region are also taking steps to protect their manufacturing bases. **Japan** has implemented an ambitious *GX policy*, with around USD 9bn dedicated to heavy industries over the next ten years. **South Korea** (*Innovation Strategy for Carbon Neutrality and Green Growth*) and **Australia** (*A Future Made in Australia Act*) are also introducing similar policies for key strategic sectors.

Other, lower-income countries usually have fewer options and adopt a pragmatic approach.

FIGURE 1.28

Production in key manufacturing areas



Data sources: Worldsteel (2023), Reuters (2013), Otto et al. (2017), Statista (2023), USGS (2023), International Aluminium (2023)

Competitive Chinese products are flooding the markets and supporting economic growth. In the *Belt and Road Initiative* (BRI), wind and solar represented the largest share of overseas investments in the first half of 2023. BRI engagements and the boost in exports helps alleviate the overcapacity issue in these industries (Baxter, 2023).

To increase local acceptability and facilitate their expansion, Chinese manufacturers are also investing abroad, mostly in the Global South. They are increasingly turning to greenfield investments, as investment screening limits M&A options and tariffs limit exports from China.

For businesses in the OECD, friend-shoring is a pragmatic option for coping with the dislocation caused by Chinese overcapacity. Some regions are trying to take advantage of the situation to develop their industries. **India** has made industry a clear priority, aiming at being an attractive destination for companies with China+1 strategies. **South East Asian** countries have become a prime location for solar panel manufacturing.

A future of subsidies?

Many economists question the wisdom of subsidising industries. A recent study showed, for instance, that on average there is a 74% probability a subsidy for a given product by one major economy is met with a subsidy for the same product by another within one year (IMF, 2024). Beyond the current turmoil, other parameters might be more decisive for future locations of manufacturing industries.

Energy costs and availability. Energy is an important expense for the manufacturing sector, especially for heavy industries. The most energy-intensive subsectors tend to be less technologically dependent and run on smaller margins. For these sectors, the price of energy (including externalities like carbon price) becomes central in decision-making to extend the lifetime of plant or build a new installation.
This was highlighted during the energy crisis following the invasion of Ukraine. Limited availability and short-term variability of natural gas and coking coal prices led to an irreversible reduction of production capacity of the European steel and petrochemical industries.

> Many economists question the wisdom of subsidizing industries. Other parameters might be more decisive for future locations of manufacturing industries.

> The ongoing global competition is about new high value-added technologies (microchips, solar PV, EVs) that are shaping future global order and the energy transition.

Value added and energy use are uncorrelated. The ongoing global competition is about new high value-added technologies (microchips, solar PV, EVs), that are shaping future global order and the energy transition. No large-scale plans really exist to relocate the manufacturing of textile, steel or consumer electronics to high-income countries.

Future demand. A large share of production capacity for energy-intensive cement or steel has been built over the last decade. Demand for these products will stabilize, and with the already existing overcapacity issue, there will be limited economic incentive to invest in multi-billion-dollar plants, and production will not move significantly. On the other hand, the production of less energy-intensive manufactured goods, with shorter investment horizons, is more flexible. Given the forecast economic growth, demand for these products will increase and there will be opportunities for new regions to build new industries.

Manufacturing ecosystems. In a less globalized world, interactions along the supply chains becomes essential, as local production has fewer export options to absorb variation in local demand. Regional steel production is for example tightly linked to the automotive industry, some 20% of steel in Europe used in that sector (Eurofer, 2024b).

Raw materials. In a deglobalizing environment, cost and access to critical materials like minerals for solar panels or batteries, iron ore for steel, or oil and gas for petrochemical products will depend on domestic production as well as geopolitical alliances.

Access to key decarbonization technologies. Progressive electrification of manufacturing means that access to low-carbon electricity at stable prices will become increasingly essential. Beyond renewable power, access to carbon transport and storage might be decisive for industries like cement, with regions with plants with limited access might have to cut production (BCG, 2024).

Skilled workforces are essential to support new industries, especially for high-tech manufacturing (WEF, 2023). Building a skilled workforce is a long-term process and is a combination of several factors like the educational system, R&D investment, and demographics. Although progress will be made in other regions, China and high-income countries will still have a competitive edge in the next decades.

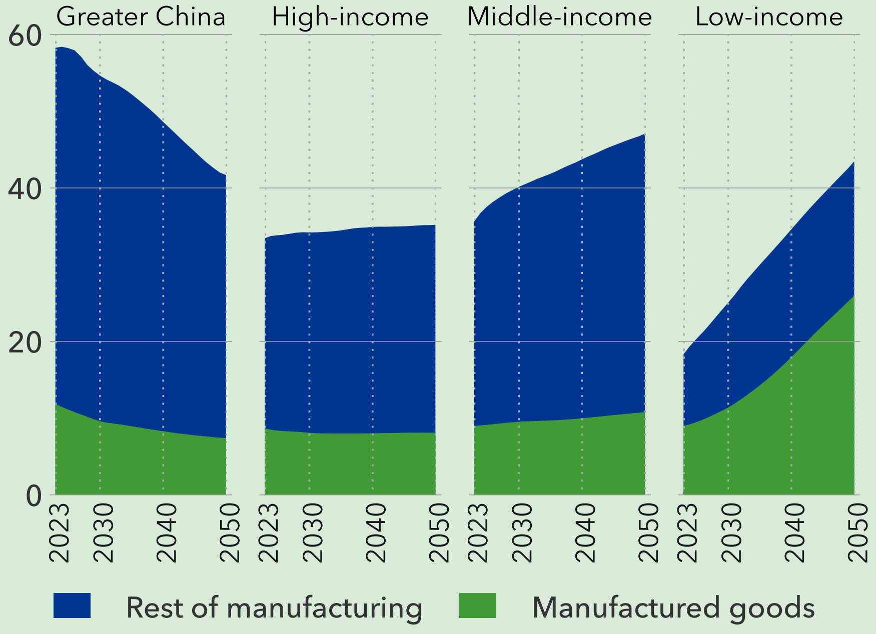
Implications for our forecast

Baking all these fast-moving geopolitical considerations in our forecast to 2050 is a challenging task, filled with uncertainty. However, we see some overarching trends taking place regionally, resulting in the following forecast demands (Figure 1.29):

FIGURE 1.29

Manufacturing energy demand by group of regions

Units: EJ/yr



- Energy demand in China will decrease as the manufacturing sector electrifies and the demand for steel and cement declines. While coal will more than halve in China's manufacturing energy mix by 2050, manufacturing in China will still use more coal than the rest of the world combined.
- OECD countries will focus the effort on high value-added steps at the end of value chains, which will not necessarily translate into a tremendous increase in energy demand.
- Some of the most energy-intensive components of new technologies (e.g. manufacturing of polysilicon for solar PV or electrodes for EV batteries) will still mostly be manufactured in other regions, namely Greater China and South East Asia.
- Manufacturing output will continue to increase in middle- and low-income countries, mainly from low-value added products, consolidating the base of their manufacturing sectors.

1.4 NON-ENERGY USE

The use of oil, natural gas, and, to a lesser extent, coal for non-energy purposes represented 41 EJ (about 8%) of global primary fossil-fuel supply in 2023. This end use will be the main growth market for oil in our forecast period.

Plastics, asphalt, and fertilizers are essential base materials. Unlike in most other sectors, no alternative to oil and gas exists at scale to produce these materials. Their demand is strongly correlated with GDP and population and the forecast growth of these two parameters means that base material demand will continue to grow. Plastics are also an important part of decarbonization given their role in turbine blades and lightweight applications. Despite these strong drivers, several trends will dampen the growth of non-energy demand:

- Increased recycling means that even though plastics demand increases by 91% to 2050, non-energy use will only rise 28%. Secondary plastics obtained by mechanical recycling covered 7% of global demand in 2023. This will grow to 27% by 2050. At the same time, the uptake of chemical recycling and similar technologies will create a stream of recycled fuel that could be directly fed into traditional steam crackers as a replacement for oil. We estimate that by 2050, 1.1 EJ of this recycled fuel will be produced each year, covering about 1% of oil primary energy demand.

- Material efficiency is the use of less material for the same application. For fertilizers for instance, technological advances, cost optimization, and soil pollution concerns in agriculture mean that the amount of nitrogen per hectare will continue to decrease as they have done in the past decades in regions like Europe (EEA, 2019).

- Reduction and substitution as alternatives to these materials exist. Concrete roads, cardboard packaging, and organic fertilizers are possible options. However, they also have drawbacks and their uptake will mostly be pushed by regulations (like the EU ban on single use plastics) rather than market decisions.

Taking into account these opposing forces, we forecast non-energy demand will continue to grow a further 13% from today's level before reaching an inflexion point around 47 EJ in the mid-2030s. From that point, demand for virgin feedstock will start slowly decreasing.

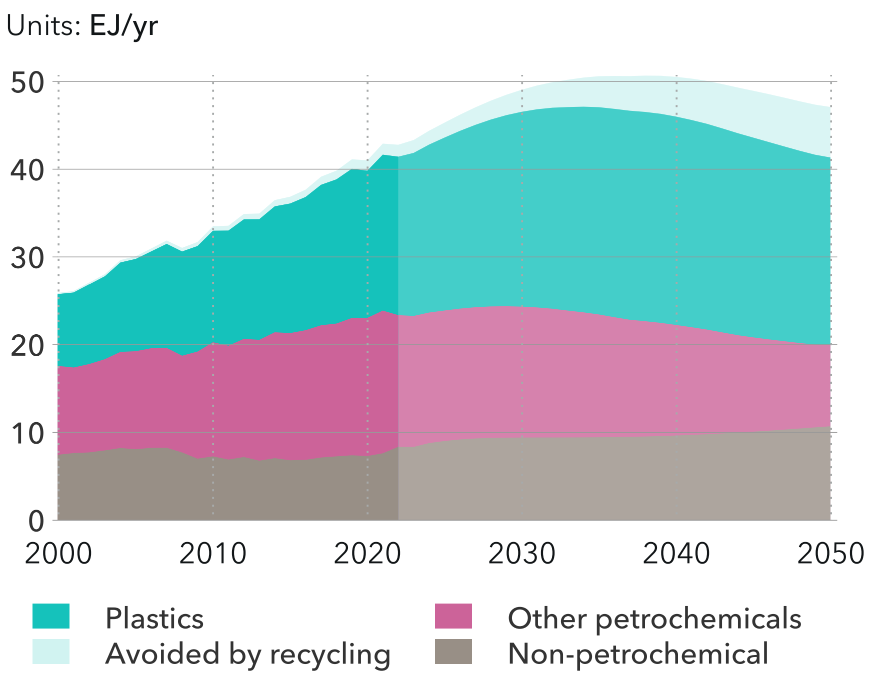
The oil and gas industry tends to view petrochemicals as a way forward as the value added is more important than for traditional energy uses. It is also a way to hedge against a world where oil demand will be declining and gasoline and diesel demand will decrease while demand for naphtha will increase. There will be a fierce competition among refineries for this growth sector. This will put an additional constraint on current production infrastructure and drive the integration of refineries and petrochemical plants (Wood Mackenzie, 2021).

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% of that, mainly for ammonia and methanol production. Feedstock choice is dependent on local availability and prices and historically installed capacity. For instance, plastics production requires primary chemicals like ethene (ethylene) or propene (propylene), which can be obtained from cracking oil or from natural gas. North America relies on natural gas 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.

FIGURE 1.30

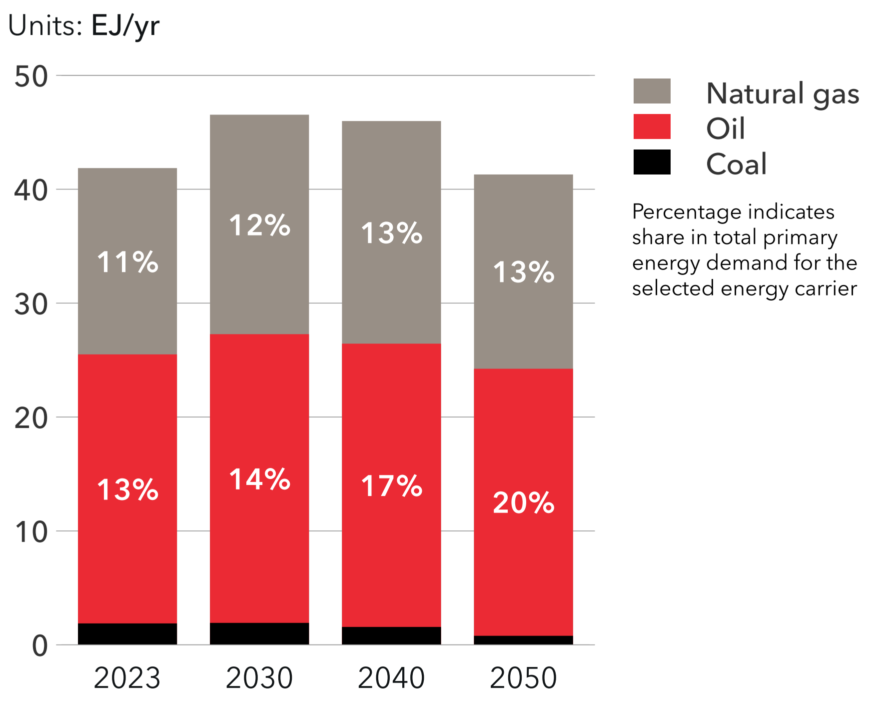
World non-energy demand by end use



Historical data source: IEA WEB (2024), DNV analysis

FIGURE 1.31

World non-energy demand for energy carriers



Percentage indicates share in total primary energy demand for the selected energy carrier

AI in the energy transition

This short section on artificial intelligence (AI) is included to set out our initial estimates on the energy footprint of AI, and to summarize our observations about the current impact of AI on energy value chains.

There is ongoing conjecture and debate about the impact of AI on the energy transition. Some argue that the 'AI Age' will accelerate the energy transition through exponential improvements to the production, transmission, and use of energy. Others argue that AI will slow the transition owing to the putatively large energy requirements of data centres and data transmission networks serving AI requirements.

We will address both perspectives in the next two sections. Before doing so, there are some framing remarks we must make.

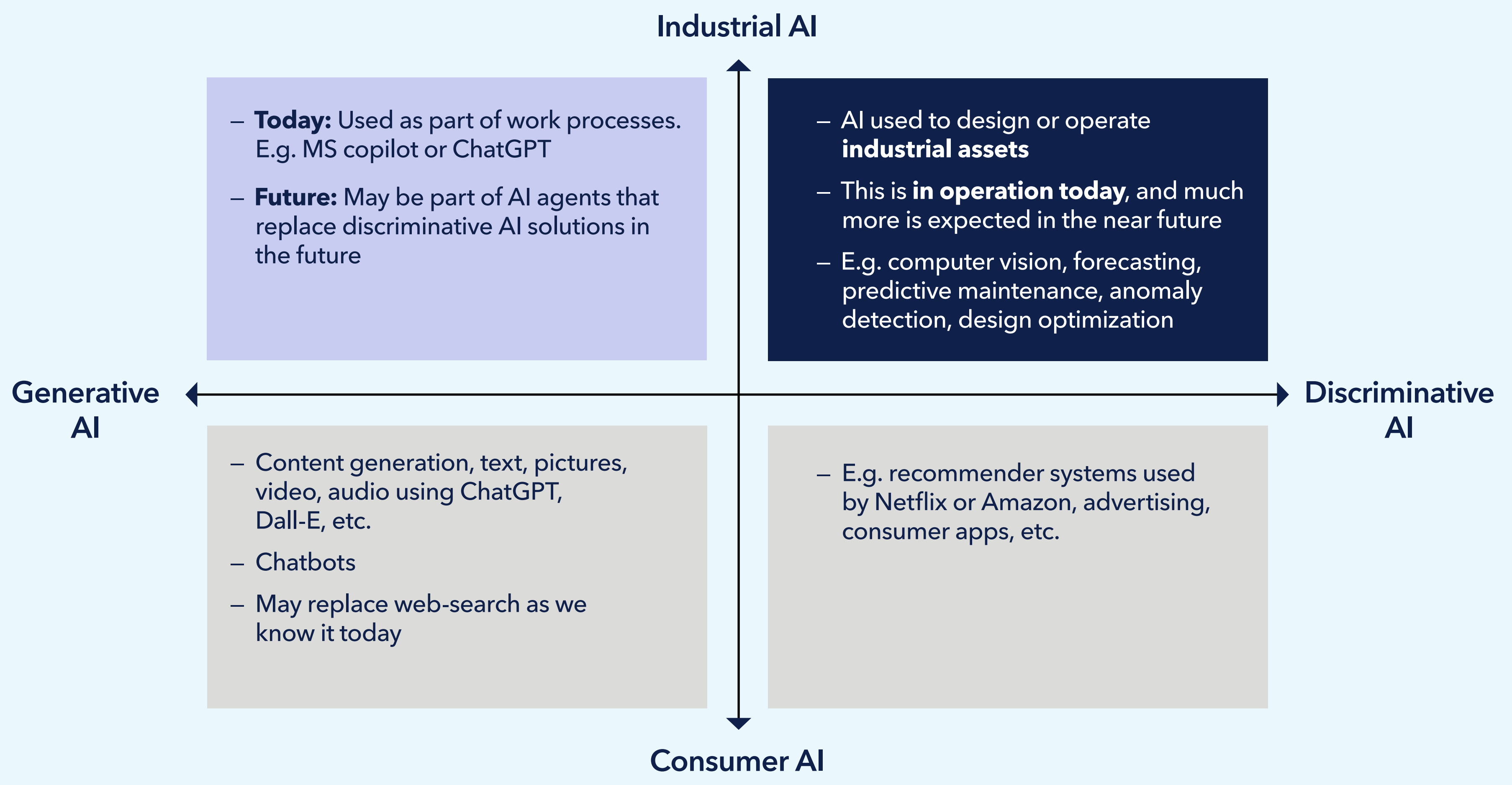
The first of these is that it is policy, and not AI, that is the main driver of the pace of the ongoing transition.

Secondly, AI can be and is being applied to oil and gas production, and as such is not the exclusive preserve of clean technology. That said, renewables are technology-led and data, learning, and algorithms from one production site tend to be applicable to others; this applies more weakly across extractive oil and gas production sites with unique geological formations.

Thirdly, AI is not new to the energy sector – it has been around since at least the 1990s – but we are now at an inflection point for the large-scale adoption of AI into the operating environments of energy systems. However, this will take time because there are significant barriers to uptake, including resistance to change and technical and cyber security considerations. From an analytical perspective, it is also very difficult to tease apart the impact of investment by energy companies in digitalization versus more specific investment in AI. Nevertheless, DNV is monitoring developments closely and we are ourselves participating in AI development for the energy industry, and leading efforts to assure AI-enabled systems.

Finally, we believe that AI is strongly subject to Amara's law: its impact is overestimated in the short term and underestimated in the long run. The hype surrounding AI at present relates mainly to generative AI and more specifically large language models (LLMs). The applicability of generative AI to energy is currently limited to low-risk applications like productivity-enhancing tools for staff like MS copilot and early experimental work. Much of the AI applicable to energy systems is not generative, but the more familiar and established discriminative AI (Figure 1.32). Discriminative AI encompasses computer vision, forecasting, predictive maintenance, design optimization, and so on. This is in operation today, and much more is expected in the future. As methods evolve to deal with the black box issues and hallucinations, generative AI will increasingly be used in industrial applications.

FIGURE 1.32



- **Today:** Used as part of work processes. E.g. MS copilot or ChatGPT
- **Future:** May be part of AI agents that replace discriminative AI solutions in the future

- AI used to design or operate **industrial assets**
- This is **in operation today**, and much more is expected in the near future
- E.g. computer vision, forecasting, predictive maintenance, anomaly detection, design optimization

- Content generation, text, pictures, video, audio using ChatGPT, Dall-E, etc.
- Chatbots
- May replace web-search as we know it today

- E.g. recommender systems used by Netflix or Amazon, advertising, consumer apps, etc.

Energy footprint of AI

It is estimated that the hardware – specifically graphics processing units (GPUs) – used to train GPT-3, the forerunner to ChaptGPT, used 1,300 MWh of electricity. That is equivalent to the energy used by 1,450 average US households each month (Foy, 2023). To put this into perspective, that energy use is a tiny sliver of, for example Microsoft's overall energy use in 2022 at 18.6 TWh in 2022 (Microsoft, 2022). Once an AI model is trained the process of running live data through it to produce a result is called 'inference' – in other words, inference is effectively the use of AI. A single inference uses a tiny amount of energy, but billions of inferences – for example the number of times that Google Translate or ChatGPT are used daily – add up. It is very difficult to get precise numbers on the energy footprint of inference, in part because different tasks have different energy footprints – discriminative tasks like text classification or extractive Q&As are much less energy intensive than generative tasks like text or image generation (Luccioni et al., 2024). However, studies from Google (Patterson et al., 2022) and Meta (Wu et al., 2022) suggest energy use is roughly split one third training and two thirds inference. In general, however, AI developers have not been releasing verified data on energy usage so building an overall picture is subject to significant uncertainties.

The training and use of AI is clearly poised to expand dramatically, with research suggesting that the AI market will exceed USD 1trn in value by 2030 – five to six times higher than today (Bloomberg, 2023). The energy footprint of AI will not grow as quickly because there are many ongoing efforts to evolve 'responsible AI' which includes large efforts to introduce efficiencies and reduce energy use. For example, at the NVIDIA GTC Conference in March 2024, CEO Jensen Huang unveiled the next-gen Blackwell GPU 'superchip' which offers dramatic performance increases for LLMs and a 25x better energy efficiency over the previous generation of GPUs (Harris, 2024). Beyond these sorts of efficiencies at processor level, other very meaningful energy savings will result from more efficient ML model architectures, better algorithms, and switching to cloud computing rather than on-premise computing, and specifically cloud computing allowing locations with cleaner, more efficient energy (Patterson, 2022).

More research is needed into growth versus efficiency factors for AI, but it is informative to look at current data centre energy use. In its *Electricity 2024* report, the IEA (2024c) estimates that 'data centres, crypto-currencies, and AI consumed about 460 TWh of electricity worldwide in 2022', almost 2% of global electricity demand. Their base case forecast for 2026 is an increase to 800 TWh, which is 2.4% of our forecast global electricity demand for that year.

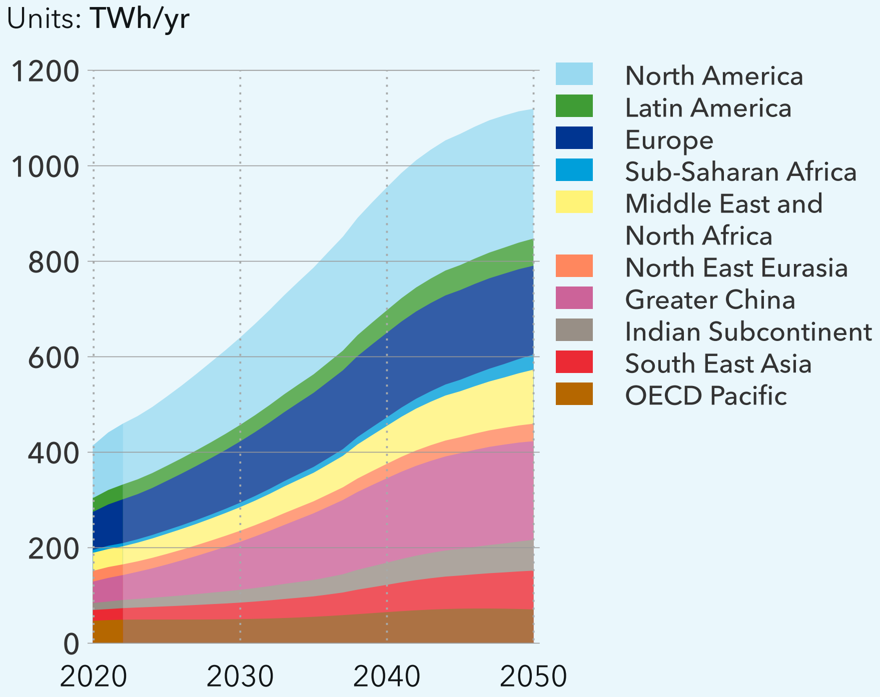
Energy use for data centres including AI falls under commercial appliances and lighting energy demand in the buildings sector of our model, and today constitutes around 7.5% of commercial appliances and lighting energy demand. Future demand takes into account growth moderated by efficiency gains. Regionally, we foresee greater demand for AI use in data centres in Europe, North America, and China, and so have applied a higher growth rate to these regions and a lower one to the rest of the world. Our higher growth rate maxes out at around 4.6% a year in 2037 and the lower rate at 2.5% a year in 2045.

This brings worldwide energy demand from Data Centres and AI to 1,100 TWh/yr in 2050, with North America leading with 24% of this energy demand in 2050, followed by China at 18%, and Europe at 17%. In the grand scheme of things, this is still a fairly small part of electricity demand; for the buildings sector it makes up just under 5% of electricity demand, and worldwide almost 2% of electricity demand. However, readers should bear in mind that, globally, electricity demand is to set to more than double between now and 2050, so we are effectively expecting AI energy use to triple in our forecast period, in spite of efficiency gains. We caution that there are large uncertainties associated with this forecast and we will address these with ongoing research. We also stress than the distribution of data centre demand is as important as absolute growth rates: it is clear that in the short term, data centres will place a strain on distribution grids in the US (Kearney et al., 2024).

The present discussion is narrowly concerned with the direct energy consumption linked to future AI developments and weighs that against expected efficiency gains at data centres etc. The grander and more meaningful discussion involves comparing AI's expected energy and emissions footprint with the many efficiencies that AI is poised to bring to everyday life, and by extension, energy use. In the next section we explore a small part of that story: the impact AI is making on the power systems value chain.

FIGURE 1.33

AI and data centre energy demand



AI advancing the energy transition

AI technology is enabling significant advancements in various areas such as power grid management, materials science, renewable energy siting, and environmental impact assessments. The examples given below are drawn from a much more detailed study by DNV on the impact digitalization and AI is already making on the power system value chain.

Power grids

For transmission and distribution system operators, AI is likely to be a game-changer. It can be used in grid planning, line routing, transformer placement, asset management, and grid operations. AI models can create synthetic data for grid planning, visualize grid designs, predict maintenance needs, and analyse sensor data to preemptively address potential issues. Utility companies like PG&E and Duke Energy use AI for infrastructure inspections and anomaly detection, enhancing network reliability and reducing downtime.

The use of AI to improve dynamic line rating will further improve the real-time assessment of power transmission lines capacity. Increasing use of sensors of both environmental factors and the current load on the line can provide a more accurate and often higher capacity rating for transmission lines.
AI models for customer load profiles have broad applications in grid modelling, demand response, and grid operations. Initiatives like the Learning to Run a Power Network (L2RPN) competitions showcase AI's potential in solving complex grid optimization problems, hinting at future AI-enabled automated grid operations (Baker et al., 2023; Behr, 2021).

Energy storage

AI significantly enhances energy storage integration with the grid, optimizing battery charge and discharge cycles, minimizing energy losses, and prolonging battery system life. DNV's Battery AI service predicts battery life based on usage profiles, and AI-driven simulations help determine the optimal size and placement of energy storage systems. Machine learning models also accelerate materials research for novel battery chemistries.

Maximizing renewable generation

Machine learning plays a crucial role in matching supply with demand, maximizing the financial value of renewable energy, and ensuring effective grid integration. Companies like Solcast provide solar irradiance data and forecasts using AI/ML algorithms, while DNV's Forecaster service employs advanced statistical methods and machine learning for short-term forecasting, covering wind and solar sites worldwide.

Siting and design of renewable generation

AI applications in siting and design optimization of renewable installations are abundant. In China, researchers developed the LightGBM machine learning model which uses satellite and sunshine data to optimize the placement of double-sided solar panels. In the US, DNV venture partner HST employs AI-based decision engines and data analytics to optimize large-scale solar installations, matching developers with energy buyers, risk management advisors, and other project partners.

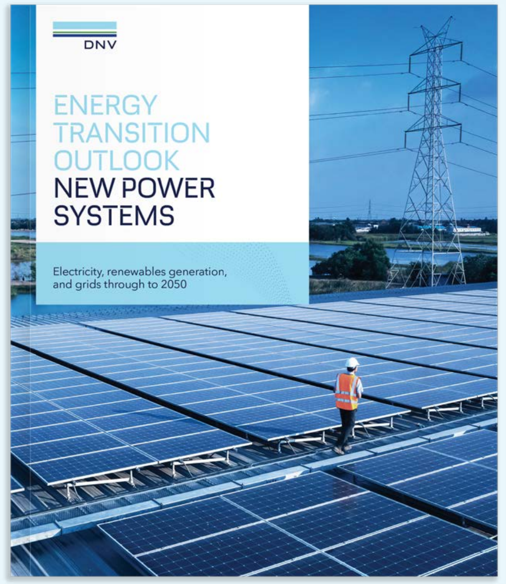
Materials science and design

AI's role in materials science and engineering is transformative, impacting materials discovery and selection for energy generation components and new battery chemistries (Papadimitriou et al., 2024). For instance, the National Renewable Energy Laboratory (NREL) in the US has used invertible neural networks to significantly accelerate the wind turbine blade design process (Vijayakumar et al., 2024). Another application is to use generative AI to evaluate different molecules for their stability, chemical properties and capacity for carbon capture to identify new approaches in molecular science for CCS projects (Park, 2024).

Permitting acceleration and environmental impact assessments (EIAs)

Complex and resource intensive approval and permitting processes can benefit from the use of AI. This could be used to leverage AI in the nuclear power sector to enhance areas such as reactor design, plant operations, and training and education. It can also be used to enhance environmental planning by utilizing sensor networks and drones for biodiversity monitoring where the technology can aid in data visualization and report generation, potentially expediting the environmental planning and permitting process. (Sandfort et al., 2024).

More detail on the current and expected impact on power systems is available in our recent *New Power Systems* report. The report also details prerequisites for AI deployment, including the main building blocks of advanced digital systems, and new approaches to AI assurance to advance safety in AI applied to critical systems and ensure compliance with, inter alia, the provisions of *EU AI Act*. Readers may also wish to consult DNV's Recommended Practice on the Assurance of AI-enabled Systems.



1.5 THE EFFECT OF ENERGY EFFICIENCY

By 2050, the global population will grow by 1.7 billion people and global GDP will increase by 89%. It is rational to assume that this will result in the world using a lot more energy in two or three decades. That is indeed the case if by 'energy' you mean useful energy – e.g. the energy used for light, heat, and car and plane trips. However, as we explain here, the world will consume only a fraction more final energy (the energy delivered to consumers' doors) to deliver all those new energy services. This is because cumulative energy efficiency gains will see humanity using raw energy a lot more intelligently.

To forecast energy efficiency and quantify its effect on the transition it is necessary to understand the differences between the terms 'useful', 'final', and 'primary' energy.

'Useful' energy stands in contrast to both 'final' and 'primary' energy (Figure 1.34). It is the energy that has been successfully converted into work, heat, light, or chemical energy, and is effectively utilized for a specific purpose, after accounting for conversion losses. 'Final energy' refers to energy directly delivered to users in forms as such as oil, gas, electricity, or hydrogen and includes both useful energy and the losses in end use. 'Primary energy' denotes its raw, pre-transformation state. Fossil fuels, for instance, can be used directly despite significant conversion losses. Secondary forms of energy, including electricity, direct heat, and hydrogen, require transformation from primary sources, whether renewable or fossil-based. Figure 1.34 charts the evolution of loss sources in the global energy system, identifying conventional thermal power generation as the chief contributor to losses between primary and final energy. Other losses stem from conversions like hydrogen production and the energy sector's own consumption, which are not included in final energy demand.

Primary energy intensity

The primary energy intensity of the global energy system, defined as primary energy consumption per unit of GDP, has steadily declined from 6.5 MJ/USD in 1980 to 3.8 MJ/USD in 2022, with an average annual reduction rate of 1.3%. Looking ahead, we anticipate energy intensity improvements averaging 2.0% annually until 2030 and 2.2% annually from 2030 to 2050. This would bring global primary energy intensity down to 3.2 MJ/USD by 2030 and 2.0 MJ/USD by 2050. However, during the 2040s, the rate of improvement slows, as further efficiency gains in power generation and energy use become harder to achieve.

Inefficiencies

Many energy-consuming systems are inherently inefficient. For example, the internal combustion engine, predominant in the transport sector, has a tank-to-wheel efficiency of only 25% to 35%. Similarly, combustion equipment such as boilers, burners, furnaces, and stoves, especially those fuelled by fossil fuels, waste about one-third of their energy. Despite continuous technological advancements aimed at reducing energy consumption, improvements are generally incremental. By 2050, we expect the average efficiency of combustion equipment to increase only marginally to around 70%. This accounts for potential technological shifts like the use of gas for cooking instead of solid biomass.

Electrification

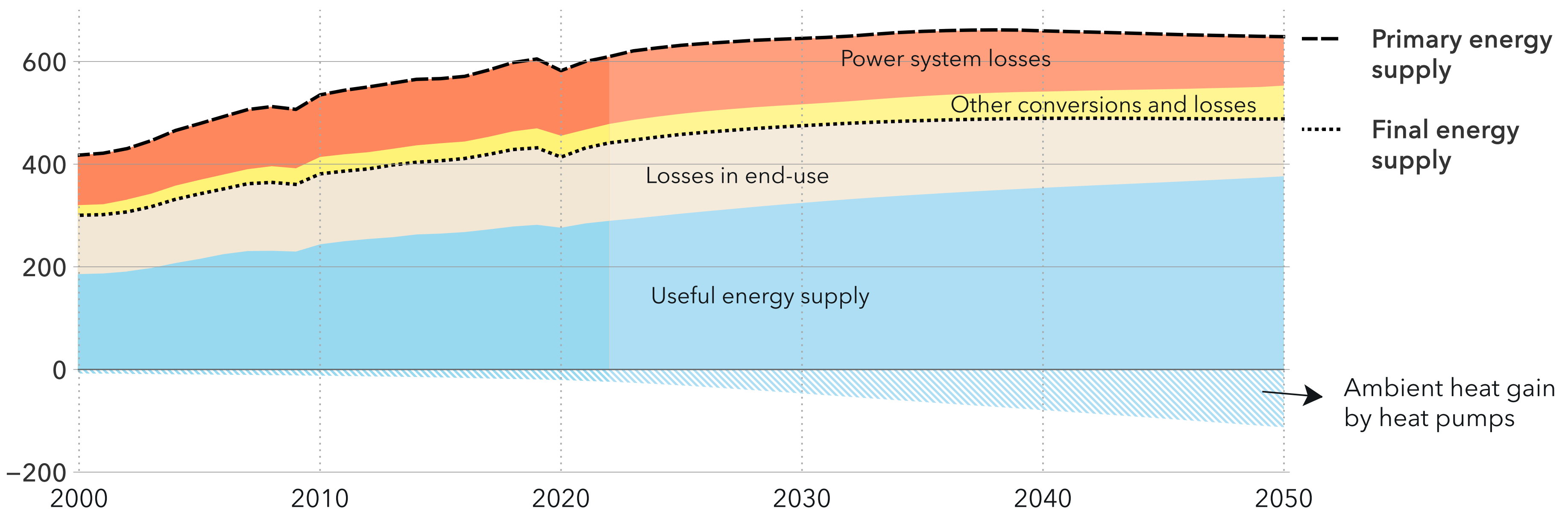
In contrast, electrical equipment like electric motors and heaters consistently exhibit high efficiencies, often exceeding 90%. Heat pumps are particularly notable for their ability to amplify input energy into a greater output of useful energy by extracting ambient environmental energy. Their coefficients of performance (CoP) often exceed 300%, meaning they can deliver more than three times the energy they consume. This potentially reinforces the idea that the push for electrification is synonymous with the push for efficiency.

We expect air conditioners, most of which function as reversed heat pumps, to be widely adopted for

FIGURE 1.34

Losses in the global energy system from primary to final and useful energy supply

Units: EJ/yr



Historical data for primary and final energy: IEA WEB (2024) space cooling by 2050. As incomes rise in previously low-income regions and electrification continues, access to cooling will expand. Combined with the challenges of global warming, this suggests that space cooling will become the primary useful energy demand category by 2050.

Historically, traditional electricity generation from coal, gas, and oil was highly inefficient and lost a lot of primary energy as heat. In 1990, the global power system efficiency was a mere 39%. However solar PV and wind directly convert electricity without heat loss, making them 100% efficient. This shift to renewables has markedly improved the conversion rate of primary energy to useful energy, from half to three-quarters, (Figure 1.34). On the other hand, nuclear energy operates at 33% efficiency when we consider the heat from nuclear fuel decay as primary energy. As renewables dominate by 2050, power system efficiency will rise from 47% today to 63%. Even with the doubling of electricity and direct heat demand from 2022 to 2050, we expect power generation losses to remain constant.

Strategies aimed at reducing energy service demand – such as insulating buildings, boosting recycling rates, or imposing congestion charges on vehicles – play a significant role in our projections. While these strategies do not directly improve the ratio of final to useful energy, they can significantly curb or negate energy consumption.

By comparing the projected useful energy demand for 2050 with a hypothetical demand that scales linearly with global GDP, we estimate that these strategies will reduce energy demand by about 80 EJ/yr (15%) from an expected 551 EJ/yr. However, potential rebound effects, such as consumers opting for larger vehicles when fuel is cheap or increasing heating use if gas prices decrease, could drive up the demand for energy services. On the other hand, the automation of energy use, particularly through AI designed to minimize consumption – whether by optimizing product design or automatically activating demand response – could yield considerable cumulative efficiency gains. Although we have not quantified this impact, which would require substantial research and modelling, one might broadly assume that the efficiencies associated with digitalization will at least offset any rebound behavioural effects.

The role of standards, policies, and initiatives

Improving energy efficiency often requires significant financial investment, typically to replace outdated equipment with modern and efficient alternatives or to retrofit existing structures for better energy conservation. While these investments promise long-term benefits in reduced energy consumption and cost savings, they can be challenging for those lacking substantial resources. This underscores the critical role of standards and policies in making energy efficiency affordable and widespread. Standards, policies, and initiatives for energy efficiency fall into eight categories:

- **Appliance and equipment standards:** Policies in this category dictate the minimum efficiency requirements for household and commercial appliances and equipment. For instance, the US Department of Energy (DOE) *Energy Policy and Conservation Act* (EPCA) prescribes energy-efficiency standards for various consumer products, ensuring they meet set efficiency thresholds. These include efficiency standards for residential refrigerators, freezers, cooking appliances, and dishwashers and are set to take effect between 2027 and 2029 in the US.
- **Building codes:** These standards establish the minimum energy performance metrics for new constructions and renovations to ensure energy conservation. The EU's revised *Energy Performance of Buildings Directive* (EPBD) exemplifies this by mandating that all new structures reach zero-energy consumption by 2030 and phasing out of fossil-fuel boilers by 2040.
- **Vehicle emission and fuel-efficiency standards:** Such policies specify both the acceptable emission levels from vehicles and their minimum fuel efficiency. For example, the *Corporate Average Fuel Economy* (CAFE) standards in the US outline strict fuel consumption norms for new passenger vehicles.
- **Utility demand-side management programmes:** These initiatives by utility companies aim to reduce consumer energy use through incentives or assistance. Programmes might include rebates for purchasing energy-efficient appliances or support for businesses that adopt energy-conserving measures in their operations.
- **Public sector initiatives:** Governments often enact these to ensure that their own operations and public structures adhere to high energy-efficiency standards. Canada's *Greening Government Strategy*, which seeks a substantial reduction in greenhouse gas emissions from federal undertakings, is one such initiative.
- **Labelling and certification programmes:** By providing consumers with clear information on a product's energy efficiency, these programmes empower informed choices. The *ENERGY STAR programme*, initiated in the US and now recognized internationally, is a prominent certification for energy-efficient products.
- **Market-based instruments:** These mechanisms encourage the adoption of energy-efficient practices by offsetting their costs. Policies might offer tax breaks, subsidies, or grants for energy-efficient upgrades. The UK's *Green Deal*, which grants loans for such enhancements repaid through energy bill savings, is an illustrative model.
- **Behavioural programmes:** Targeting the way individuals and entities utilize energy, these initiatives promote energy-conserving habits. Japan's *Cool Biz* campaign encouraging lighter workplace attire to diminish air conditioning use showcases this approach.

1.6 FINAL ENERGY DEMAND

Combining the final energy demand for all demand sectors, the most noticeable change in the next 25 years is the growing role of electricity in final energy demand. Electrification is both pivotal to decarbonization and key to unlocking considerable efficiencies within the global energy system.

In 2023, electricity represented 20% of world final energy use (Figure 1.35). By mid-century, this will be 36%, with electricity demand doubling from 91 EJ per year in 2023 to 181 EJ in 2050, averaging 2.6% growth annually. Electricity will steadily replace other forms of energy use with the sum of all final energy use that is not electricity reducing 0.5% per year in the same period.

The importance of electricity is greater than its 36% share indicates; with higher efficiency in its end use than the other energy carriers, we can safely say that more than half of all energy services in mid-century will be provided by electricity. The growth happens in all sectors: buildings, manufacturing, and strongest within road transport.

Technology, cost, and policy all contribute to the rapid rise of electricity. With superior efficiency, electricity has an inbuilt advantage over other energy carriers. An oft-repeated piece of general advice is to 'electrify whatever can be electrified'. Cost reductions for wind and especially solar power have been significant and are expected to continue, further driving the economic attractiveness of electricity relative to all other fuels. New applications requiring electricity are emerging – for example, data centres and air conditioning. Additionally, because electricity is fairly easy to decarbonize compared with other energy carriers, ever more ambitious decarbonization policies inevitably turn to electricity.

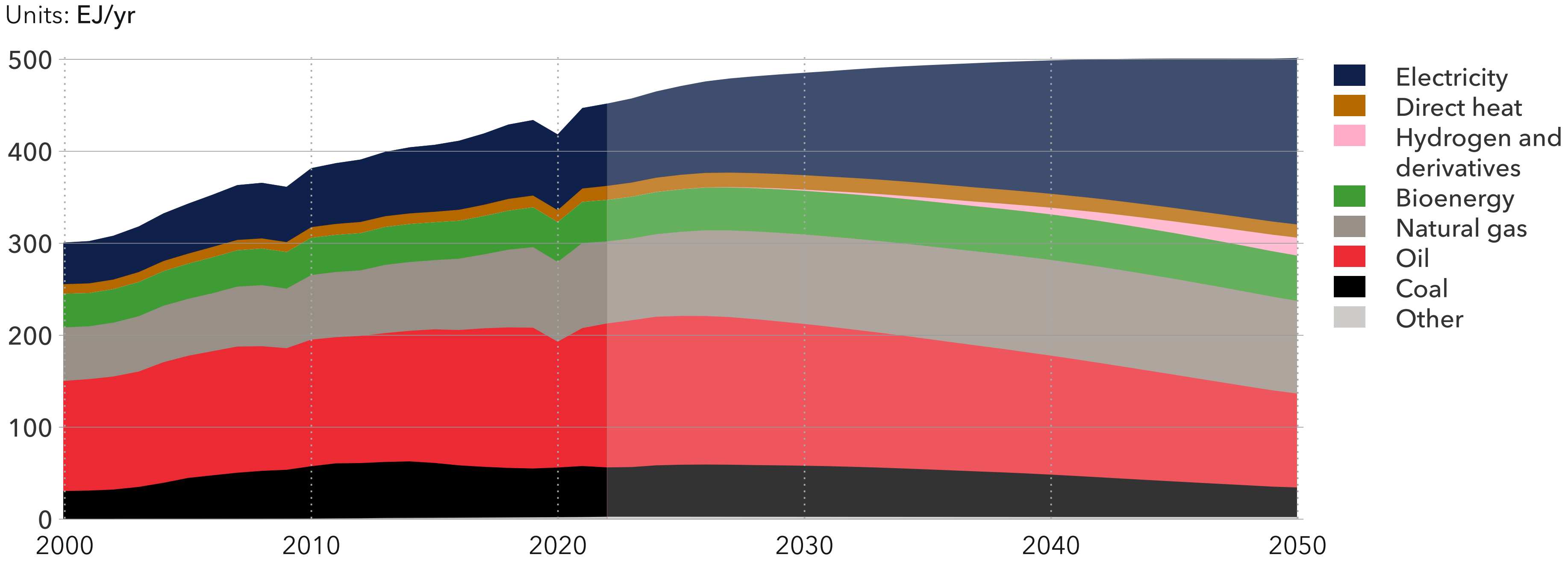
Hydrogen and hydrogen derivatives also show significant growth in our ETO forecast, but they start from a very low base. From a negligible contribution today, they will reach 1.4% of final energy demand in 2040 and 4% by 2050. Hydrogen has an important, but relatively niche role to play in the energy transition.

Direct use of biomass and heat delivered directly as a commodity (direct heat) both remain more or less constant at 10% and 3%, respectively, of global energy demand throughout our forecast period.

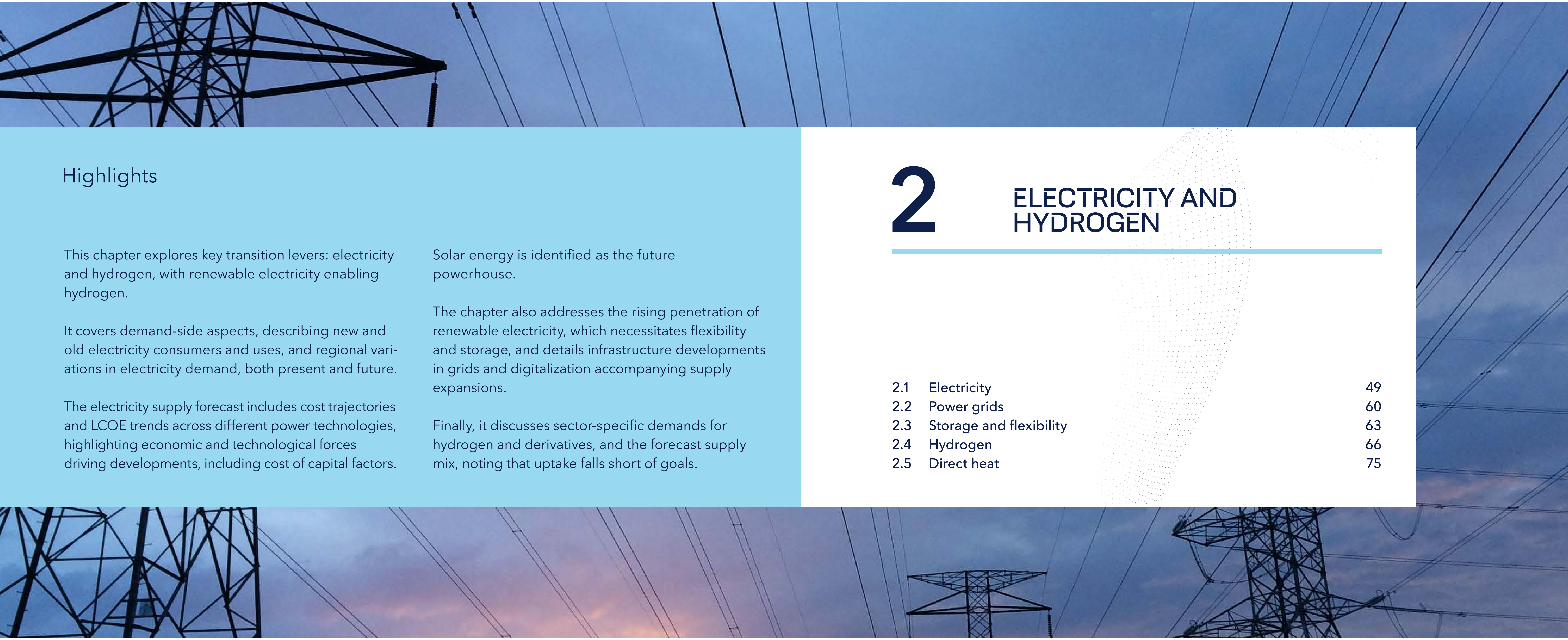
The decline in direct use of fossil fuels is less than the decline of fossil fuels found in electricity production, reducing from 66% of final energy use today to 47% in 2050. Direct use of oil and of coal both decline about 40% through to 2050. Direct use of natural gas, however, increases modestly through the forecast period, coming from growth in buildings and manufacturing.

FIGURE 1.35

World final energy demand by carrier



Historical data source: IEA WEB (2024)



2

ELECTRICITY AND HYDROGEN

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Highlights

This chapter explores key transition levers: electricity and hydrogen, with renewable electricity enabling hydrogen.

It covers demand-side aspects, describing new and old electricity consumers and uses, and regional variations in electricity demand, both present and future.

The electricity supply forecast includes cost trajectories and LCOE trends across different power technologies, highlighting economic and technological forces driving developments, including cost of capital factors.

Solar energy is identified as the future powerhouse.

The chapter also addresses the rising penetration of renewable electricity, which necessitates flexibility and storage, and details infrastructure developments in grids and digitalization accompanying supply expansions.

Finally, it discusses sector-specific demands for hydrogen and derivatives, and the forecast supply mix, noting that uptake falls short of goals.

2.1 ELECTRICITY

The growing and greening of electricity is the standout feature of the energy transition. Not only will electricity demand double globally between now and mid-century, but power will be 90% decarbonized by then. The growing dominance of variable renewables – solar and wind – will see the need for short-term flexibility quadruple and the rise of new market mechanisms and technologies that will allow demand to follow supply. With bidirectional power flows and millions of new distributed energy resources that generate, store, and consume power, grid operations will become increasingly complex and impossible to manage without substantial digitalization upgrades. Grid capacity will grow by some 2.5 times. While newbuild transmission and distribution infrastructure is planned and under construction, grid enhancing technologies (GETs) will be needed to get the most out of existing equipment and rights of way. The result of these substantial investments and transformations will be a system that brings clean, efficient, and modern energy to almost every individual on this planet.

2.1.1 Electricity demand

Global electricity demand is on track to more than double during our forecast period, rising from 30 petawatt-hours (PWh) in 2023 to 61.6 PWh by 2050, driven by its increased use in buildings and the electrification of transport and industrial processes.

The doubling of electricity demand is the result of several transformative changes across sectors. One of the primary drivers is the electrification of transport. By 2050, an estimated 2.5 billion EVs will be on the roads, requiring 6.2 PWh of electricity annually. This transition is not just about replacing petrol and diesel with electricity; it also involves a broader change in the power system that includes an increased need for flexibility, more distributed generation, and opportunities created by the new uses of electricity.

In the industrial sector, electricity is essential for powering machines, motors, and appliances that produce a vast array of goods. As economic activities fluctuate, so does electricity consumption. Developing countries – for example, India and Indonesia – in particular are experiencing increased mechanization, leading to a surge in electricity demand as manual processes become automated. Additionally, the adoption of electric heating, especially through industrial heat pumps, is set to create new demand for low-temperature processes.

Buildings are also becoming significant consumers of electricity, driven by population growth and rising living standards. Electricity powers everything from lighting and refrigeration to entertainment and cleaning. While efficiency gains – such as from LED lighting – are reducing consumption in some areas, new sources of demand are emerging. For instance, the global south is witnessing a surge in air conditioning usage, which we expect to add 5.4 PWh to annual electricity demand by 2050. In higher-latitude countries, heat pumps – which we project to be the primary heating source in about a third of households – will demand an additional 1 PWh globally.

Costs of solar and wind generation and battery storage will continue to fall throughout our forecast period. As renewables start to supply a growing share of a country's power mix, market designs – for example time-of-use charges – will need to develop to allow consumers to benefit from these lower cost technologies. Indeed, advanced tariff mechanisms that enable automated demand response as well as prosumers and vehicle-to-grid schemes will become important markers of how efficiently and competitively nations manage their energy transitions. Taxes and levies that discourage the uptake of electricity in favour of fossil energy will come to be seen as increasingly inimical to decarbonization pledges. On a more positive note, widespread electrification may present policymakers with opportunities to address social inequalities through mechanisms like rising block tariffs – with the rate per unit of electricity increasing as the volume of consumption increases, which incentivizes investment in energy efficiencies by the heavier power users.

Hydrogen production, another emerging demand, will require 1.9 PWh of electricity by 2050 as electrolysers connected to the grid harness cheap, abundant solar and wind power. This development underscores the growing interdependence between renewable energy and flexibility provided by new electricity applications, further driving co-dependent growth of renewable supply and flexible demand.

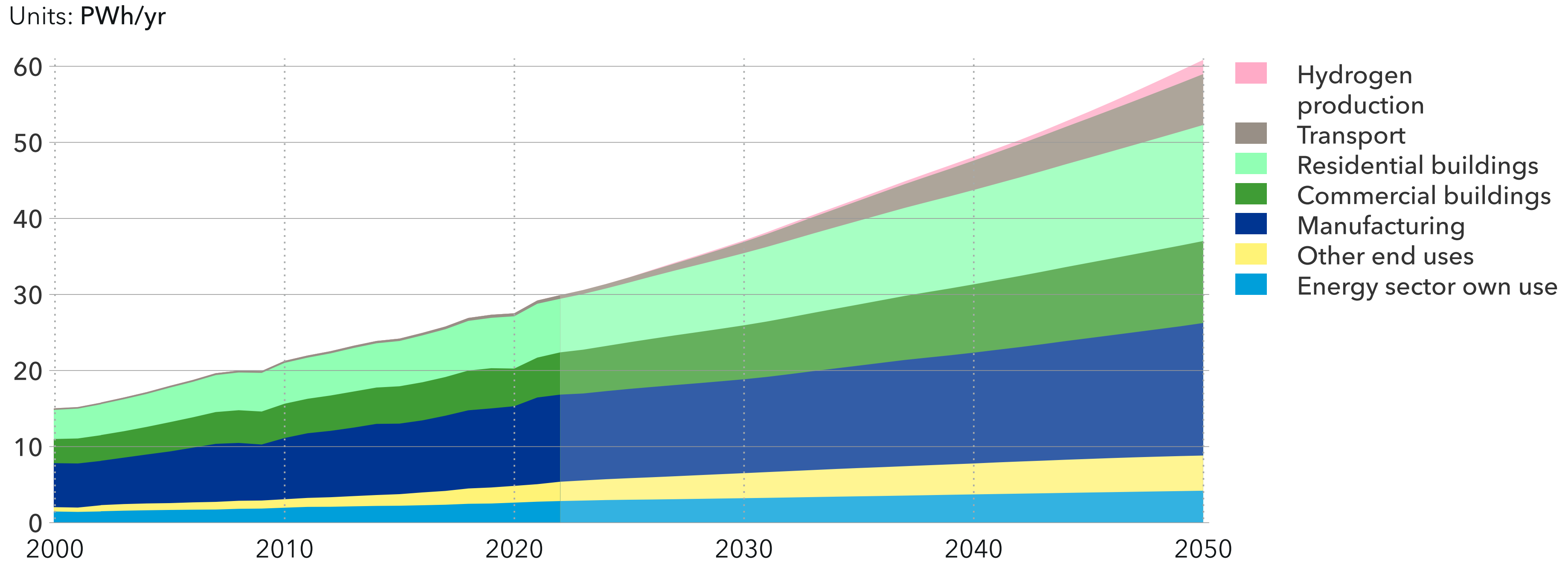
Regional variation in electricity demand

Electricity demand growth and mix varies by region (Figure 2.2).

North America's electricity demand is projected to grow by 64% between 2023 and 2050, with an annual growth rate of 1.8%. This growth, moderate compared to other regions, reflects the region's already high electrification levels. The key drivers for demand will be the growing adoption of EVs and the increase in buildings electricity demand. The rise in

FIGURE 2.1

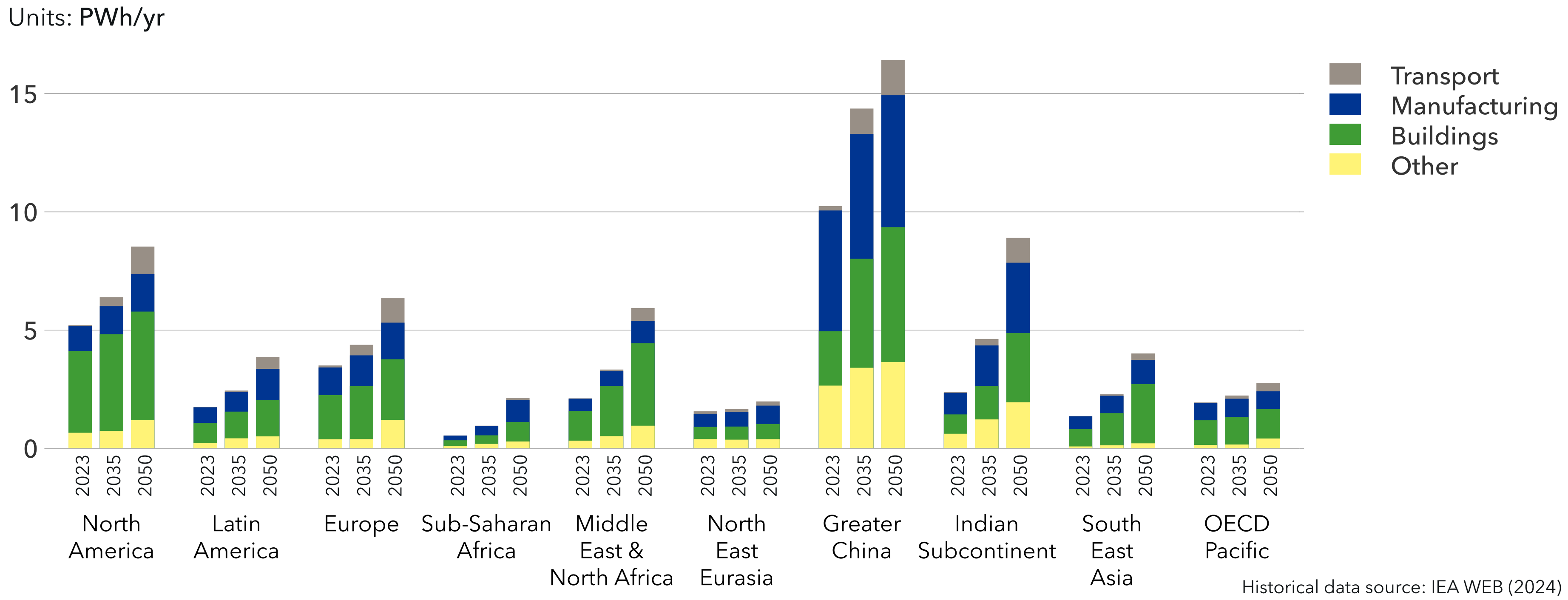
World annual electricity demand by segment



Historical data source: IEA (2024), DNV analysis

FIGURE 2.2

Electricity demand by region



Historical data source: IEA WEB (2024)

building demand is partly due to expansion of data centres, although the overall growth rate is tempered by slow population growth and energy efficiency gains in mature sectors including the switch to high-efficiency equipment like heat pumps.

Latin America will likely see a substantial 121% increase in electricity demand from 2023 to 2050, translating to an annual growth rate of 3.0%. Growth is propelled by rising electrification in residential and industrial sectors, coupled with population growth and economic development. Notably, we anticipate the region's cooling and appliances needs will surge due to rising living standards, urbanization, and global warming. The industrial sector's electricity demand is set to nearly triple, especially in countries like Brazil and Mexico where manufacturing is expanding.

Europe's electricity demand is on course to grow by 81% by 2050, with an annual growth rate of 2.2%. Despite the continent's focus on energy efficiency and decarbonization, new demand will emerge from the electrification of transport and heating and from the production of low-carbon hydrogen via electrolysis. We expect the shift towards EVs and the decarbonization of heating to be the most prominent drivers of this growth. Europe's push for low-carbon hydrogen will result in hydrogen electrolysis consuming 12% of total electricity demand by mid-century.

Sub-Saharan Africa will experience the highest growth rate globally, with electricity demand surging 294% by 2050, an impressive annual growth rate of 5.2%. This rapid expansion reflects the region's low base of current electrification combined with expected economic growth and population increase. The region presents significant potential for electrification, especially in its expanding industrial activity and in the growing use of electricity by households for appliances and cooling.

Middle East and North Africa is projected to see a 181% increase in electricity demand by 2050, with an annual growth rate of 3.9%. The main drivers will be the growing demand from hydrogen production and end uses like air conditioning and desalination as a result of climate change and population growth. Additionally, the region's economic diversification efforts, particularly in the Gulf states, are likely to boost industrial electricity consumption.

North East Eurasia is expected to have the slowest growth in electricity demand, with an increase of only 27% by 2050, reflecting an annual growth rate of 0.9%. This sluggish growth is largely due to stagnant population metrics and slow economic growth in countries like Russia. However, there may be some increases in demand driven by the industrial and hydrogen sectors, particularly in the context of energy exports and the potential for increased electrification in rural areas.

Greater China's electricity demand is forecast to grow by 60% from 2023 to 2050, with an annual growth rate of 1.8%. While this growth is significant in absolute terms, it represents a deceleration compared to previous decades that reflects the region's maturing economy and slowing population growth. The transport sector, particularly EVs, will continue to be a significant driver, while much of the potential for electrification in other sectors has already been realized. The biggest growth in demand will come from space cooling, where AC penetration and utilization in urban areas will continue to increase.

The Indian Subcontinent will witness a massive 273% growth in electricity demand by 2050, with an annual growth rate of 5.0%. This extraordinary expansion is driven by rapid urbanization, industrialization, and a push for universal electrification. The cooling and industrial sectors will be the primary contributors to this growth – reflecting both rising incomes and a young, growing population – but growth in electricity

demand will be observed in all segments, including transport and agriculture, thanks to the mechanization of farming and the need for electric irrigation systems.

South East Asia's electricity demand is expected to increase by 194% by 2050, corresponding to an annual growth rate of 4.1%. This robust growth is driven by economic expansion, urbanization, and a massive demand for cooling and appliances. The region's ongoing industrialization and increasing electrification in rural areas will also play a crucial role in shaping demand patterns. The industrial sector, particularly in countries like Indonesia and Vietnam, is expected to see a tripling of electricity demand as manufacturing expands.

The OECD Pacific region, including countries like Japan and Australia, is projected to see a modest 42% increase in electricity demand by 2050, with an annual growth rate of 1.3%. The region's demand growth will be tempered by slow population growth and strong energy efficiency measures. However, new demand will emerge from the electrification of transport and for hydrogen production as renewable energy sources become more prominent, particularly in Australia.

> This is not just a shift in fuel sources, but a re-imagining of how power systems operate.

2.1.2 Electricity supply

The global power system is undergoing a dramatic transformation, reshaping the way electricity is generated, distributed, and consumed. As we approach 2050, the energy landscape will be defined not just by a shift in fuel sources, but by a reimagining of how power systems operate across different regions.

Renewable energy is on a rapid ascent. From its 2023 level of 9.2 PWh/yr, renewable electricity generation is set to rise steeply by 15.2 PWh/yr by 2035 (Figure 2.3). However, this surge in clean energy does not immediately translate into a reduction in fossil fuel use.

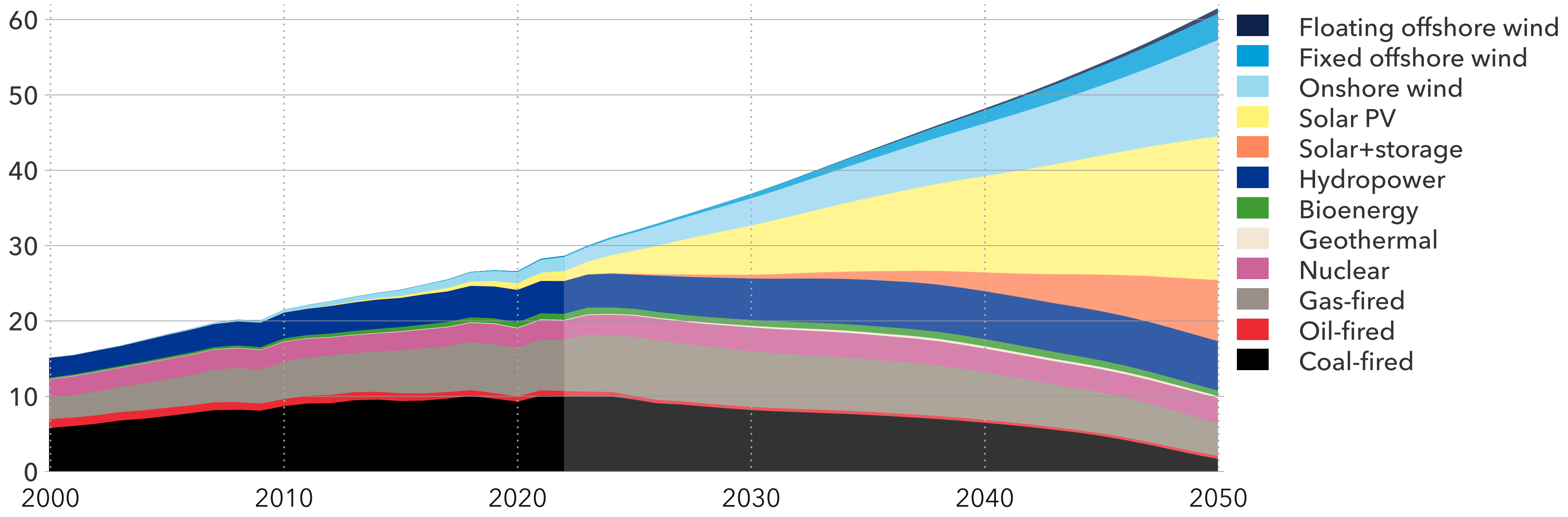
The world's growing appetite for electricity – set to rise by 12.1 PWh/yr in the same period – means that much of this new renewable capacity will be absorbed by fresh demand. It is only in the late 2030s that we can expect renewables to outpace this rising demand, setting the stage for a more meaningful decline in fossil fuel reliance.

This shift is powered by economic forces as much as technological ones. Solar energy is emerging as the powerhouse of the future; its costs are plummeting and its reach is expanding. By 2050, we project solar will dominate the global power mix, capturing a substantial 44% share. The key to solar's success is not just in its daytime generation but in the growing

FIGURE 2.3

World grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2024), GlobalData (2024) sophistication of storage technologies that allow solar power to be used around the clock, making it a more reliable source of energy.

> Solar energy is emerging as the powerhouse of the future; its costs are plummeting and its reach is expanding.

Wind energy is another crucial piece of the puzzle, although its growth story is somewhat different. Wind power, while generally costlier than solar, has the advantage of potential 24-hour generation, especially in regions with strong and consistent winds. By mid-century, we expect wind to supply 28% of global electricity, with significant contributions from both onshore and offshore installations. Offshore wind, in particular, is poised for significant growth driven by its reliability and the relative freedom from land constraints. With annual growth rates of 12% expected for offshore wind until 2050, it's clear that this sector will play a pivotal role in the future energy mix.

The shift towards renewables could significantly alter global geopolitical dynamics. Countries that are traditionally dependent on imported fossil fuels could achieve greater energy independence by harnessing their local renewable resources. This could potentially reduce geopolitical tensions related to energy supply. For instance, Europe's push towards wind, solar, and hydrogen will lower its reliance on energy imports from volatile regions. On the other hand, fossil fuel-exporting regions such as the Middle East and North Africa and North East Eurasia may face economic and political challenges as global demand for oil and, to some extent, natural gas dwindles.

Some regions are also likely to remain tethered to fossil fuels for their own consumption, largely due to financial constraints and the slower development of renewable infrastructure. For instance, coal will continue to be a dominant power source in China until 2030, while the Indian Subcontinent and South East Asia are likely to use coal for some of their electricity generation beyond 2050. Natural gas will also remain a key player, especially in the Middle East and North Africa and in North East Eurasia where it will continue to dominate power generation for the next two decades. Chapter 8 provides more details about the power generation mixes of the regions.

The global energy transition is not just about replacing one energy source with another; it is about a fundamental reshaping of the entire power landscape. As solar and wind rise to prominence, traditional power stations are being recast in new roles. No longer the dominant players, these conventional plants will increasingly serve as the grid's safety net, providing critical backup and stability when the sun isn't shining or the wind isn't blowing. Even as fossil fuel electricity generation is set to plummet by 65% by 2050, the infrastructure will largely remain intact, with only a modest 12% reduction in capacity. This means that most fossil thermal plants will remain operational and will not be shuttered; they will operate much less frequently, but their large capacities and ability to quickly ramp up generation make them indispensable, especially as the grid becomes more complex and variable. However, the concept of base-load power, long the foundation of electricity supply, may fade away to be replaced by a more dynamic, flexible grid.

Cost trajectories

The Levelized Cost of Energy (LCOE) has long been a crucial metric in evaluating the cost-effectiveness of power station investments. It measures the average cost of producing a megawatt-hour (MWh) of electricity over the lifespan of a power station. As global energy dynamics shift, understanding the LCOE trends across different technologies is essential for assessing future energy strategies.

Solar photovoltaic (PV) and wind power have emerged as the most competitive sources of electricity in many regions, driven by significant technological advancements. In solar, improvements such as higher-efficiency cells and automated manufacturing processes have substantially reduced material waste and production costs. The wind sector has benefited from the development of larger and more efficient turbines that lower costs by generating more power per unit. The entry of Chinese manufacturers into these markets has intensified competition, further driving down prices. Moreover, the production scaling and more efficient installation processes have led to cost reductions in both technologies. Lower financing costs also play a crucial role, making these renewable projects more affordable.

By 2030, we expect the global average LCOE for solar PV to fall below USD 30/MWh, with the addition of on-site storage pushing the cost to around USD 55 to 60/MWh. Between 2030 and 2050, it will decline by 1.2% annually to reach USD 22/MWh at the end of our forecast.

Similarly, we project the 2030 global LCOE for onshore wind to be approximately USD 42/MWh, with fixed offshore wind at about USD 110/MWh and floating offshore just below USD 300/MWh. Onshore wind will see a 2.1% annual reduction, with costs reaching USD 28/MWh by mid-century. Fixed offshore wind costs will remain above USD 67/MWh on average, though they could drop to USD 40/MWh in optimal locations. Floating offshore wind will maintain a cost premium of around USD 28/MWh over fixed offshore wind by 2050, but sites with favourable conditions – such as consistent high winds and proximity to shore – could see competitive LCOEs for floating offshore wind.

Hydropower costs are heavily influenced by site-specific factors: geological conditions, project scale, engineering challenges, and regulatory considerations. As regions like Europe and China exhaust the most favourable locations, future capacity additions will likely be concentrated in areas with untapped resources such as Latin America, the Indian Subcontinent, and Sub-Saharan Africa. We expect this shift to cause a modest reduction in the global weighted average LCOE for hydropower by 2050.

Conventional power stations, such as coal and gas, face limited opportunities for further technology-driven cost reductions. As a result, factors such as fuel costs, carbon pricing, and capacity factors will predominantly determine their future LCOEs. Coal-fired power stations are experiencing rising LCOEs due to declining capacity factors, while gas-fired power maintains a relatively steady LCOE in the range of USD 60 to 120/MWh through our forecast period, supported by a lower carbon footprint and strategic shifts to regions with more affordable gas supplies. Readers will notice how the average LCOE of gas falls away from the price surge in the early 2020s but starts climbing again to breach the USD 100 mark in the 2040s. The uptick is largely explained by the effect of carbon pricing, which has a more nuanced impact of gas than coal but nonetheless does produce a visible change.

Nuclear power presents a more complex picture. The cost data is often skewed by a small number of projects and, in developed countries, cost overruns have led to rising LCOEs. However, as the balance of nuclear power shifts towards China and India and considering the long-term potential of small modular reactors, we expect the average cost of nuclear to decline to USD 70 to 80/MWh. This will be supported in part by shorter construction times and more favourable borrowing terms, with some projects potentially reaching as low as USD 50/MWh. Section 3.4 gives more insights into the nuclear industry.

The real-term cost of capital – the return required by investors to fund power projects – is a critical factor in the LCOE equation. It reflects investor perceptions of risk across different technologies and regions. A higher cost of capital raises the overall financing cost of a project, thus increasing the LCOE. As the perceived risk of stranded assets grows and public sentiment shifts, we expect the cost of capital for fossil-fuel power stations to rise. Conversely, mature

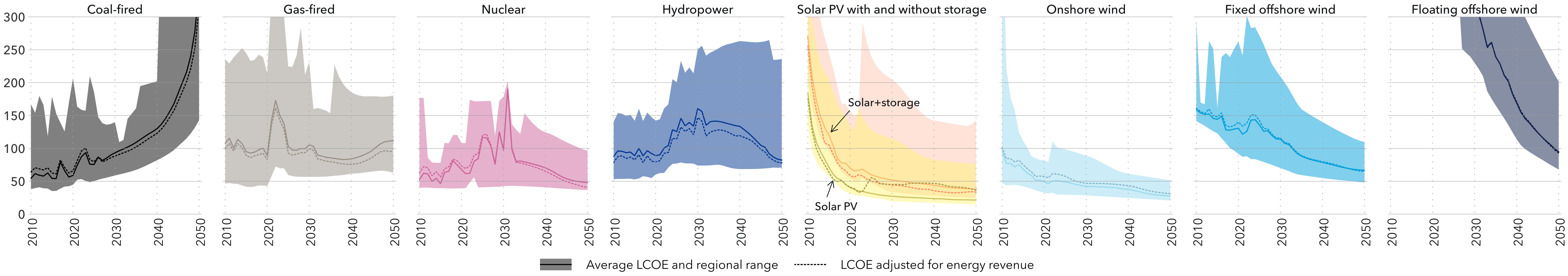
Revenue-adjusted LCOE

While the levelized cost of energy (LCOE) has been the main metric in assessing the competitiveness of technologies, its inability to reflect revenues makes it an incomplete measure for determining future investments. We use the energy-revenue adjusted LCOE to overcome this problem (Figure 2.4). This metric accounts for the difference between a technology's annual average capture price and the prevailing wholesale price. Such adjustments ensure that technology earnings align with market demands.

FIGURE 2.4

Average levelized cost of energy (LCOE) by power station type

Units: USD/MWh



renewables – e.g. hydropower, bioenergy, solar, onshore wind, and bottom-fixed offshore wind – typically benefit from the lowest costs of capital, a trend that is likely to continue. Emerging technologies, like floating offshore wind and energy storage, currently carry higher risks and thus face higher borrowing costs, though we expect this gap to narrow over the next 10 to 15 years. See Chapter 5 for a more detailed analysis of cost of capital projections across different energy sources.

In addition to using revenue-adjusted LCOE (see sidebar) we also take into account the fact that power stations may receive compensation for ensuring a certain portion or all of their capacity is available during times specified by the system operator. This arrangement, known as a 'capacity market', underpins grid reliability and ensures adequate capacity during peak demand. As variable renewables grow, we anticipate a rise in these capacity markets. Emerging flexibility markets, which are not yet widespread, will likely become key in future power systems. Such flexibility markets compensate power producers and storage operators for their ability to rapidly adjust electricity output in response to grid demands. In our model, we segment these markets – energy, capacity, and flexibility – distinctly. When there is a gap between demand and supply of energy, it can spur new investments, with the revenue-adjusted LCOE acting as a guide to identify the most cost-effective technologies. We also compute similar metrics for capacity and flexibility to influence the mix of new investments.

> Emerging flexibility markets, which are not yet widespread, will likely become key in future power systems.

Near-term challenges

The global power sector is still coping with the aftershocks of supply chain disruptions triggered by the COVID-19 pandemic and ongoing geopolitical tensions, particularly between the US and China. These disruptions have led to increased costs for essential components like semiconductors and transformers and slowed the deployment of new technologies and the maintenance of existing systems. For example, the prices of key raw materials – such as copper and steel – have surged, leading to higher manufacturing costs and delays in project timelines.

Recently, the copper market has seen a shift towards a surplus thanks mostly to increased production capacity, particularly in China where smelting and refining activities have expanded significantly (Laurence, 2024). We expect this surplus to continue through 2024 with the potential to lower prices. In contrast, the steel market is recovering more slowly. Although there is some new production capacity, especially in Asia (Featherstone Partners, 2024), the sector is still grappling with the impacts of previous disruptions. The steel industry also faces pressure to decarbonize, which could increase costs and slow down capacity expansion. This will potentially keep prices elevated in the near term. However, we do not anticipate a significant price surge unless there are further supply disruptions or unexpected spikes in demand.

Power systems in many developed regions, such as the US and Europe, are increasingly burdened by ageing infrastructure that requires upgrades and maintenance. In the US for instance, the average coal plant is over 40 years old and much of the transmission infrastructure was installed several decades ago. This leads to frequent failures and inefficiencies. Similarly, countries like Germany and the UK face significant challenges with their ageing grid infrastructure which has already resulted in reliability issues and rising maintenance costs.

The transition to more advanced, renewable-based power systems also necessitates a workforce skilled in digital technologies, data analysis, and renewable energy. In Europe and North America, there are already emerging shortages of skilled labour, particularly in areas like offshore wind technology and grid management. For instance, the rapid expansion of offshore wind farms in the North Sea has outpaced the availability of trained technicians and engineers, leading to project delays and increased labour costs. This shortage is exacerbated by competition from other sectors, such as technology and construction, which require workers with similar skill sets.

The growing digitalization and interconnectivity of power systems has also heightened their vulnerability to cyberattacks. A stark example is the 2015 cyber-attack (Zetter, 2016) on Ukraine's power grid which caused widespread outages affecting nearly 250,000 people. This incident highlights the critical need for robust cyber security measures; breaches can lead to severe disruptions, economic losses, and even threats to national security.

Finally, inconsistent regulatory frameworks also stand as a challenge in the short-term, especially in regions with unclear or shifting policies on carbon pricing and renewable energy targets. In the US, for example, the fluctuating policy landscape regarding federal subsidies for renewable energy has created uncertainty for investors. This has resulted in delays in project financing and deployment. Similarly, ongoing revisions to the EU's carbon trading scheme have left utilities and investors uncertain about long-term cost implications, slowing the adoption of clean energy technologies.

Can we maintain a stable and reliable electricity supply with a high proportion of variable energy sources like solar and wind?

Ensuring future power systems' adequacy – the ability to consistently meet demand – remains crucial, especially with the rising integration of variable renewable energy sources and changing consumption patterns. Figure 2.5 illustrates this challenge, presenting simulated electricity supply and demand distributions for Europe in 2023 and 2050. Unlike the current system, the most pressing adequacy challenges in 2050 will not occur during hours of high demand but during periods of low solar and wind output.

Our simulations show that in 2050, the highest projected residual load in Europe – the gap between demand and renewable generation – will not exceed 620 GW. This gap can be managed through a combination of 220 GW of hydropower, 300 GW of thermal power, and 100 GW from various storage technologies that include standalone batteries and vehicle-to-grid systems available at the peak residual load hour.

However, several challenges could complicate this scenario. Our simulations are based on an average weather year; the peak residual load could be higher than 620 GW in a year with more extreme weather conditions. Additionally, grid constraints might prevent the full capacity of hydropower, thermal power, and storage from being available exactly when and where it is needed. This could lead to localized shortages even if the total capacity is theoretically sufficient.

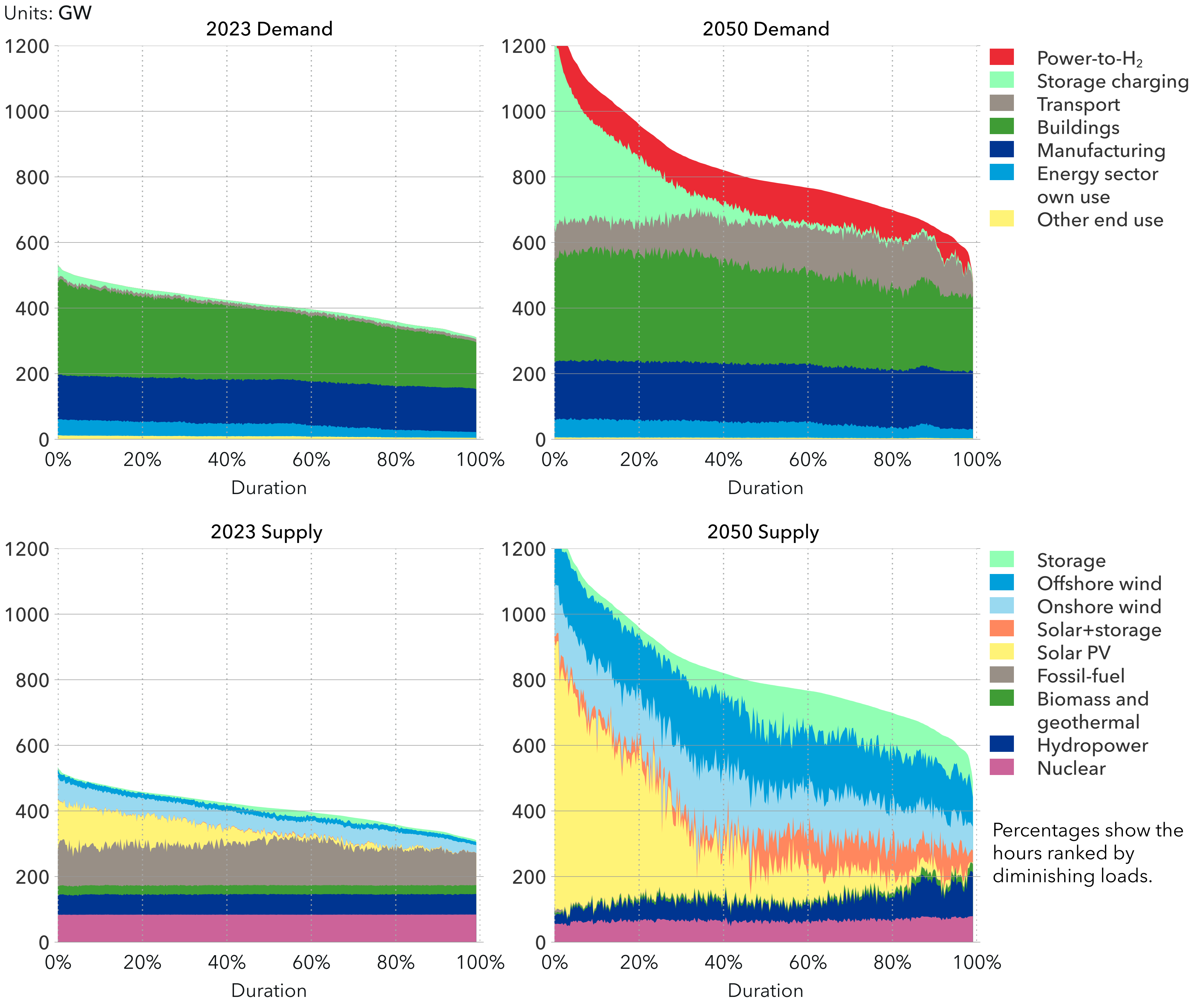
Despite these potential challenges, it is important to note that our analysis has not accounted for the contributions from the over 1.1 TW of solar+storage capacity that we forecast will be installed across Europe. This additional capacity will enhance the system's ability to meet demand and maintain adequacy. To ensure that our forecast is consistent with future adequacy needs, our model ensures the system has enough firm capacity and triggers investments if any gap arises.

Future power systems will likely be designed with more accurate and economically efficient safety margins. Rather than relying solely on conservative estimates that heavily favour dispatchable generation, planners will consider the full potential of renewable energy and storage technologies. This will lead to a more balanced and cost-effective system design.

Beyond ensuring adequacy, several technical and operational challenges must be addressed to maintain a stable and reliable electricity supply with a high proportion of variable energy sources like solar and wind.

FIGURE 2.5

Load-duration curves for European electricity supply and demand in 2023 and 2050



The curve displays Europe's aggregate supply and demand, organized by total load. For clarity, hours are grouped, not plotted individually. This grouping causes the appearance of solar PV output at all times, even during hours when Europe has no solar generation due to lack of sunlight. Curtailed output is not shown.

One critical issue is frequency stability. Traditional power systems rely on large, synchronous generators that are typically powered by fossil fuels to maintain grid frequency through their rotational inertia. This inertia helps to dampen fluctuations in frequency caused by sudden changes in supply or demand. However, solar and wind generators – especially those connected to the grid via inverters – do not naturally provide this inertia. Frequency control challenges typically arise when variable renewable energy sources (VRES) penetration exceeds 50% of total electricity generation (Mararakanye and Bekker, 2019), as the reduction in conventional synchronous generation decreases system inertia. At these levels, the grid becomes more sensitive to frequency fluctuations. Batteries can play a crucial role in addressing this issue by providing fast frequency response services, which help stabilize the grid almost instantaneously after a disturbance. Unlike conventional generators, which can take minutes to adjust, battery storage systems can react in milliseconds, offering a rapid solution to frequency deviations.

Another concern is voltage control. Maintaining voltage levels within a narrow range is essential for the stable operation of the grid. Traditional power plants can adjust their reactive power output to help manage voltage, but solar and wind farms typically do not have this capability without additional equipment. As the proportion of these renewables increases, the grid will need new mechanisms to manage voltage, such as the installation of flexible alternating current transmission systems (FACTS) and the widespread deployment of distributed energy resources with voltage control capabilities.

Grid congestion is another significant issue. As renewable energy sources are often located far from demand centres – e.g. offshore wind farms or solar farms in remote desert areas – the transmission network can become congested. This leads to inefficiencies and potential reliability issues. Although our model does not explicitly resolve such spatial congestion problems, we account for the need to expand and upgrade transmission infrastructure to accommodate the increased load and ensure that power can be transported efficiently from where it is generated to where it is needed.

Operational flexibility will also become increasingly important. As solar and wind power generation is inherently variable, grid operators need to be able to ramp other sources of generation up or down quickly to balance supply and demand. This requires a mix of flexible generation assets – such as natural gas peaker plants – and the development of advanced demand-side management programmes that can adjust consumption patterns in real-time – such as vehicle-to-grid systems. Additionally, the integration of energy storage systems, which can absorb excess power during periods of high renewable output and release it when output drops, is essential for providing the required operational flexibility. Section 2.3 expands on the future needs and providers of flexibility.

How will we manage the excess power generated during periods of high renewable output?

One of the primary methods to manage surplus renewable output is through energy storage, which can absorb excess electricity and release it when demand is higher. Technologies such as Li-ion batteries, long-duration batteries, and vehicle-to-grid systems play a significant role here by enabling price arbitrage – where electricity is stored when prices are low (due to surplus renewable generation) and sold when prices are high. Moreover, the development of electrolysers that convert surplus electricity into hydrogen provides a flexible option for using excess power in different sectors, such as transportation and industry. This approach not only stabilizes the grid but also creates new revenue streams, making renewable energy more economically viable. The infographic below on the hourly power market modelling illustrates the role electrolysers may play.

The need for large-scale seasonal storage is limited, particularly in systems where full decarbonization is not mandated. The economic case for such storage is weak, as oversupply during high renewable output can be effectively managed by utilizing electrolysers to produce hydrogen. Any excess beyond this can be curtailed without significant impact. For times of high residual load, it is more efficient to store gas and use gas peakers briefly rather than stored electricity. Globally, we expect hydrogen to contribute only 0.05% to power supply by 2050, as storing and converting hydrogen back to electricity is costly and inefficient unless heavily subsidized by governments for decarbonization or to support hydrogen development. The main contribution of hydrogen to new power systems lies in the creation of revenue streams for excess renewable power through the indirect electrification with green hydrogen of hard-to-electrify sectors.

Will the financial incentives be strong enough to drive the necessary expansion of both generation and storage?

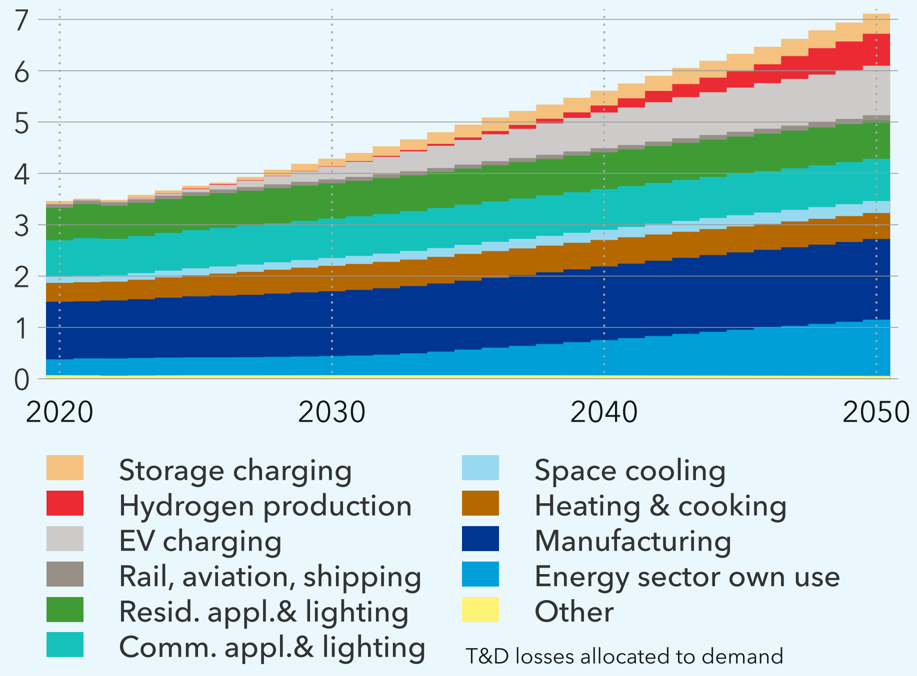
The financial incentives for expanding both generation and storage are currently in place but they face challenges, particularly in the form of price, cannibalization for renewables like solar PV. As the market penetration of variable renewables increases, the capture price for these sources tends to decrease, potentially reducing their attractiveness to investors. However, the integration of storage solutions with renewable generation can mitigate this effect, as storage allows for better price management by taking advantage of price fluctuations. We expect technologies that combine renewable generation with storage – such as solar+storage systems – to remain financially competitive, especially as storage costs continue to decline. Additionally, direct financial incentives – such as government subsidies, tax breaks, and compensation for ancillary services like frequency control – will play a crucial role in maintaining investor interest. These incentives will need to be carefully designed and adjusted over time to ensure they effectively drive the necessary expansion of both renewable generation and storage capacities.

MODELLING POWER HOUR BY HOUR

Here we illustrate how our hourly power dispatch model operates with reference to region Europe and year 2050.

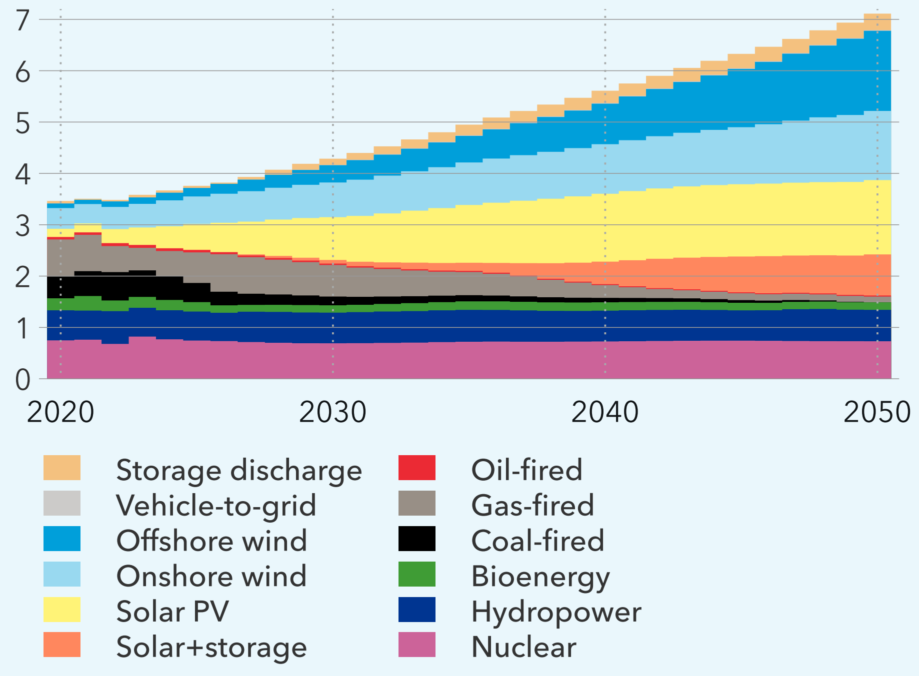
Annual electricity demand by segment comes from the corresponding parts of the model. Investments for new capacity is based on energy, firm capacity, and flexibility needs. Technology mix is decided by revenue-adjusted levelized cost.

In the figure below, we expand the year 2050 over 52 weeks. Solar, wind, and heating/cooling load profiles fluctuate over the year. Dispatchable generation and storage react to price. All profiles are aggregated over Europe. Winter's low solar output is offset by higher wind and seasonal flexibility from conventional generation and power-to-hydrogen.



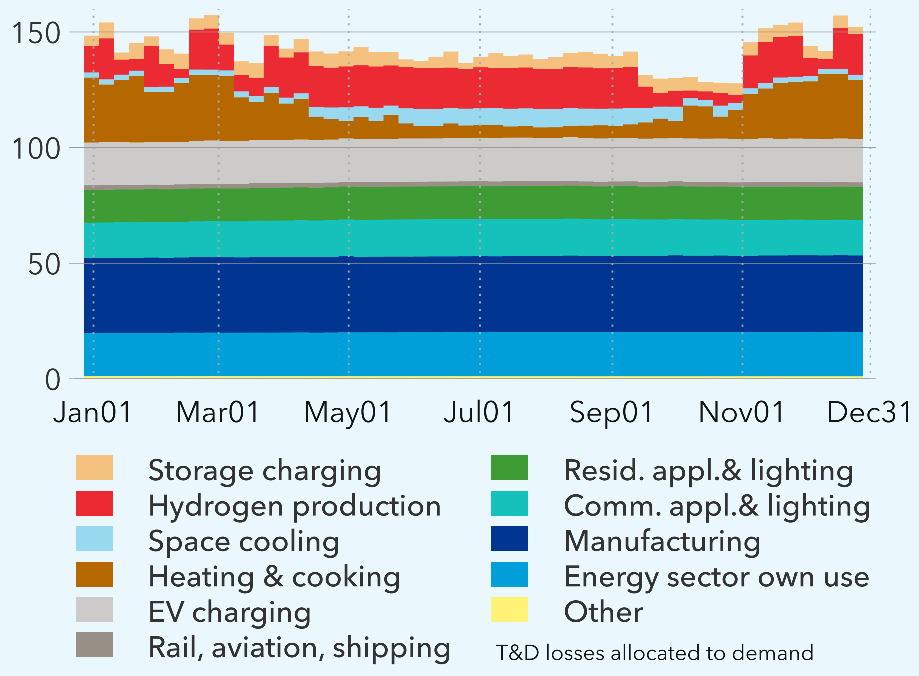
Europe electricity demand by segment; 2020-2050

Units: PWh/yr



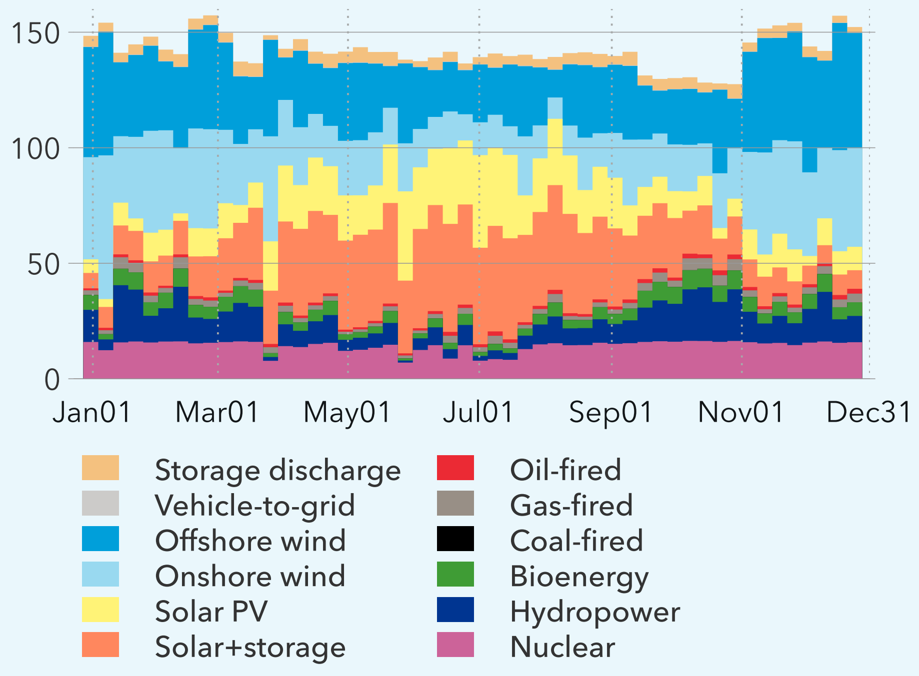
Europe electricity supply by source; 2020-2050

Units: PWh/yr



Europe electricity demand by segment; 2050

Units: TWh/week



Europe electricity supply by source; 2050

Units: TWh/week

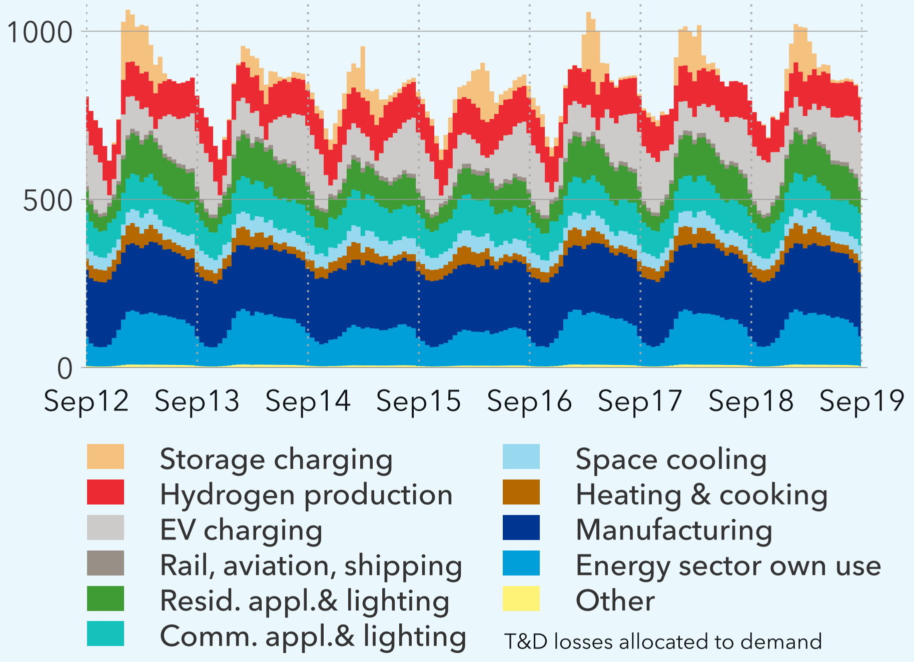
MODELLING POWER HOUR BY HOUR

The chart below focuses on week 37. Storage and hydrogen production respond to price signals. During midday, with abundant solar and cheaper electricity, electrolysis plants run and storage charges. At night, stored electricity is released while solar+storage plants provide power.

Hourly, the model sets demand and supply curves, representing them at every price (shown below). The intersection of these curves reveals the actual supply, demand, and price.

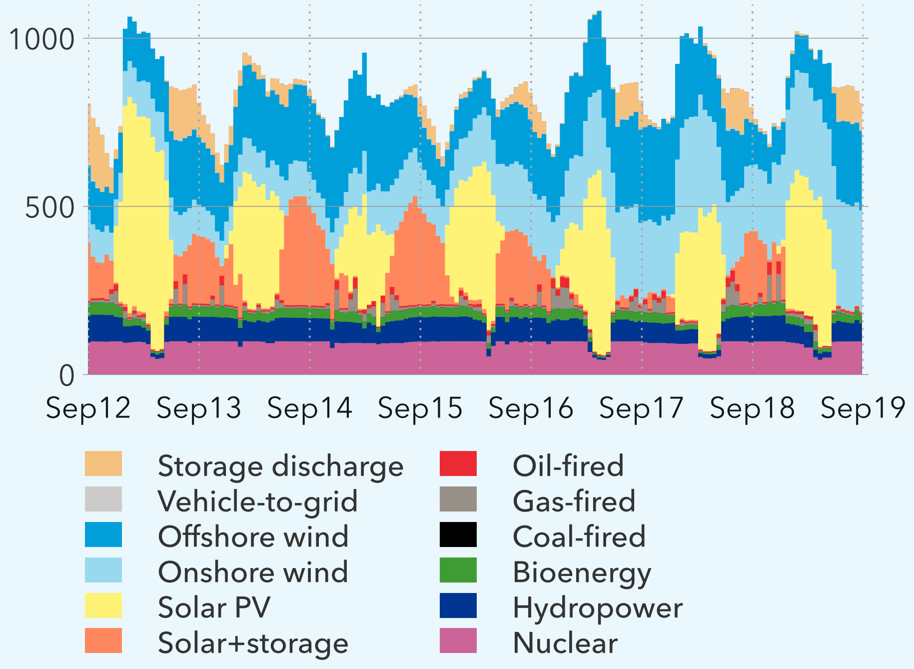
Europe electricity demand by segment; week 37; 2050

Units: GWh/hour



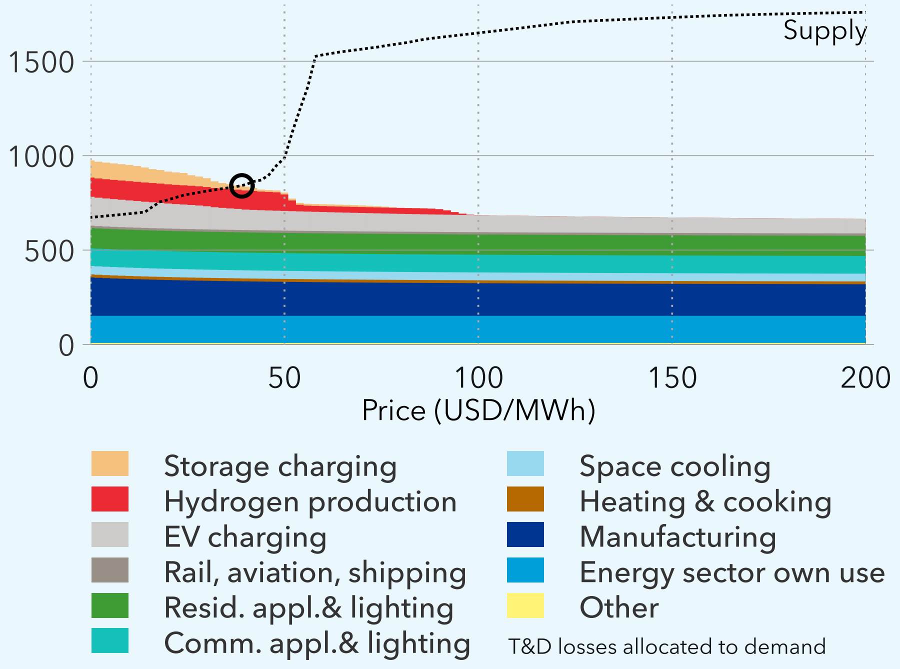
Europe electricity supply by source; week 37; 2050

Units: GWh/hour



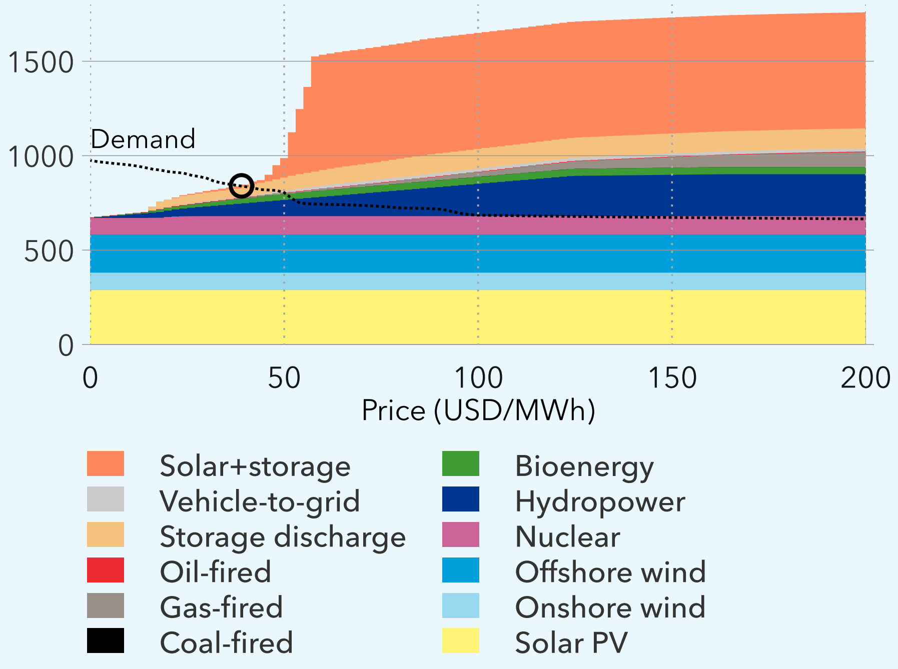
Europe electricity demand curve; 13 September 2050; 17:00-18:00

Units: GWh/hour



Europe electricity supply curve; 13 September 2050; 17:00-18:00

Units: GWh/hour



2.2 POWER GRIDS

We project the global transmission and distribution grid length will double from 104 million circuit kilometres (c-km) in 2023 to 215 million c-km by 2050. This 3% annual growth rate exceeds the pace of electricity demand growth and is largely driven by years of under-investment in ageing grids across various regions. Additionally, we expect grid capacity to expand 2.5 times within the same period to connect growing supply and demand. To support and accelerate the renewable energy transition outlined in our ETO forecast, the grid must undergo significant transformation that integrates advanced grid enhancement technologies, digitalization, and AI.

National and regional transmission and distribution grids that move power across vast distances and through complex networks are sometimes described as the largest machines ever built. Transmission encompasses high-, extra-high-, and ultra-high-voltage (collectively referred to as high voltage, HV) power lines; transformers; control centres; and more. These systems transport electricity from power plants over long distances at high voltages to minimize losses. Meanwhile, distribution grids – which consist of low- and medium-voltage power lines and step-down transformers – deliver electricity to various demand centres, including homes and factories.

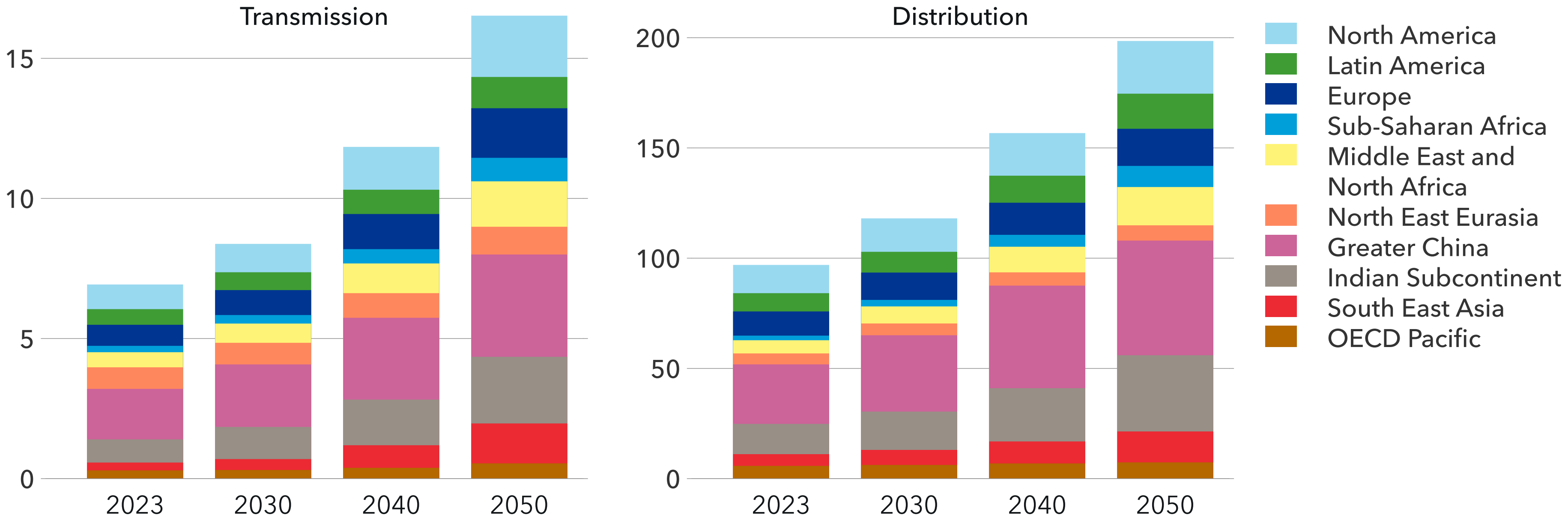
The power grid is fundamental to the energy transition because it is crucial for connecting the growing number of greenfield renewable projects, which are often located in remote areas, to both existing and emerging demand centres. Figure 2.6 illustrates the projected growth in transmission and distribution line lengths across different regions between 2023 and 2050.

> We expect grid capacity to expand 2.5 times between 2023 and 2050.

FIGURE 2.6

Transmission and distribution power-line length by region

Units: Million circuit-km



Historical data source: GlobalData (2024), DNV analysis

Distribution grid

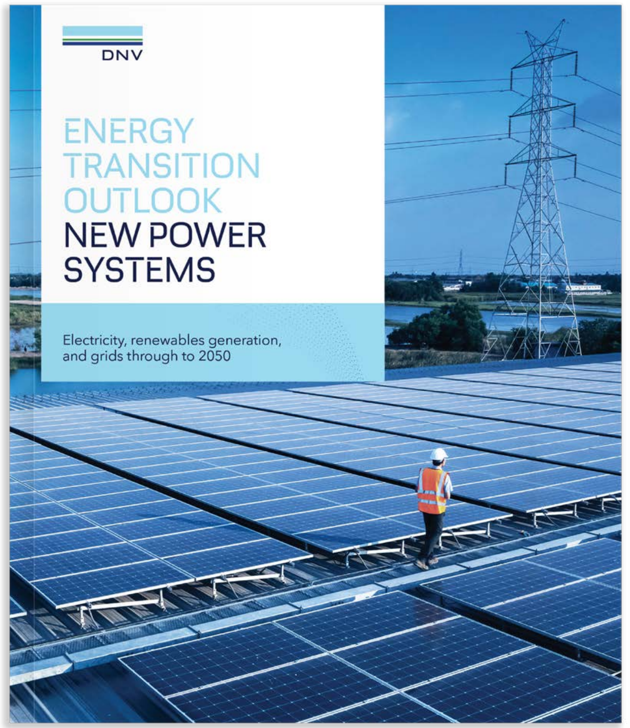
We project a global doubling of distribution line length, from 97 million c-km in 2023 to 196 million c-km by 2050 (Figure 2.6). While this growth is significant, regional disparities play a key role in driving this expansion. For example, we expect distribution line lengths in the Indian Subcontinent and Sub-Saharan Africa to triple and quintuple, respectively, over the next three decades as these regions continue to expand electrification to underserved areas. In regions like North America and Europe, despite their current near-universal electrification, it is new electricity demand categories, such as data centres and EV charging infrastructure, that will drive growth in distribution line lengths.

Additionally, increasing demand from sectors with distinct seasonal variations, such as space cooling / air conditioning and space heating, drives higher peak power demand which in turn amplifies the need for enhanced grid capacity. This trend is reflected in the growth of distribution grid capacity, which we project to expand from 207 TW-km in 2023 to 510 TW-km by 2050, representing a 2.5-fold increase. Notably, this growth in capacity outpaces the increase in distribution line length, underscoring the importance of getting the most out of both existing and planned new distribution grid infrastructure.

The operation of distribution grids will become much more complex in the future with the growth of bidirectional flows and the need to incorporate millions of new distributed energy resources (DERs – e.g. rooftop solar, microgrids, microturbines, and so on). This increasing complexity necessitates the implementation of digitalized grid operations enhanced by AI. Tools like dynamic stability assessments enable operators to evaluate the grid's response to dynamic events, such as sudden load changes, faults, or generator trips. These technologies play a critical role in enhancing grid reliability and security by ensuring that power systems can withstand disturbances while maintaining stable operation.

The expansion of distribution grid capacity, resilience, and security within existing infrastructure depends heavily on regulations and policies that incentivize proactive investment by Distribution System Operators (DSOs) in digitalization, including AI and, crucially, enhanced cyber security. This includes, but is not limited to, upgrading control centre systems, substation automation, the roll out of smart meters, and systems capable of handling the automated activation of demand-response. The goal should be the ability of DSOs to operate distribution grids close to their physical limits while optimally interfacing with DERs to ensure that those resources enhance grid flexibility without imperilling stability.

For further insights into distribution line capacity growth, congestion management, grid resilience, and AI, we direct our reader to DNV's *New Power Systems* report (DNV, 2024), published in June 2024.



DNV
ENERGY TRANSITION OUTLOOK
NEW POWER SYSTEMS
Electricity, renewables generation, and grids through to 2050

ETO New Power Systems report

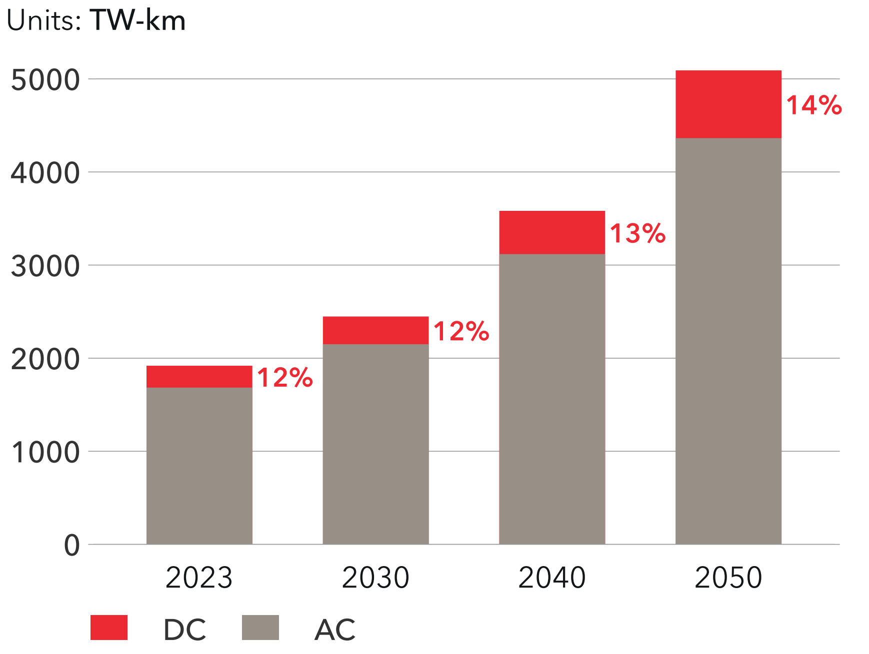
Transmission grid

We forecast the transmission grid will grow from 7 million c-km in 2023 to 17 million c-km by 2050, globally. Most of this growth will be to accommodate and connect the new renewable sources that will come online in all regions. In terms of global transmission capacity, we expect the grid will grow 2.7 times from its current state of 1900 TW-km to 5,100 TW-km by 2050.

As with the distribution grid, there are key regional differences in transmission grid growth. As expected, regions with high demand growth and new power plants coming online have higher growth. South East Asia is the leader with a 5-fold increase from 2023 to 2050. Surprisingly, we expect even North America and Europe, two regions with advanced electricity grids, to double transmission grid length due to the deeper electrification of their economies and to the enormous amount of renewable power that will be connected to the grid. The windier and sunnier generating sites in these regions are often far from population centres, requiring long transmission lines to deliver their power to demand centres. Along with expansion, we expect to see infrastructure being modernized and refurbished, especially in North America where 70% of transmission lines are more than 25 years old (DOE, 2023).

FIGURE 2.7

Transmission grid capacity by type of current



Historical data source: GlobalData (2024), DNV analysis

The growth in transmission grid capacity delivered by alternating (AC) and direct current (DC) is shown in Figure 2.7.

The upfront costs of DC are higher than for AC. However, DC is less costly on the basis of electricity transmitted per distance and has lower voltage losses. By 2050, we forecast 15% of the transmission capacity will be HVDC lines. An important sub-category of these is under-sea cables that will connect offshore wind power plants to inland demand centres, amounting to 15,000 c-km in 2050, about 1% by transmission grid length.

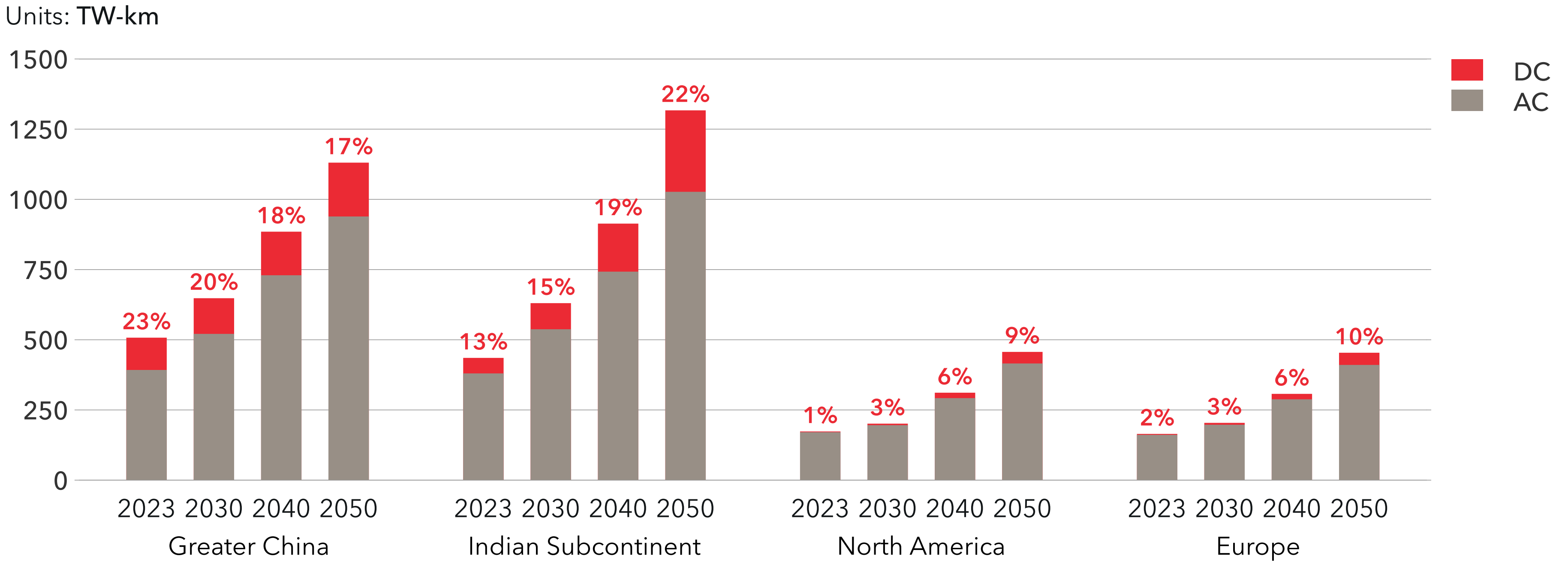
Over the next three decades, more and more DC transmission lines will come online. However, they will do so at different rates across regions (Figure 2.8). Greater China currently has the highest capacity of HVDC lines of all world regions, and we expect it to maintain this leadership position in the future. However, we forecast the highest growth in the Indian Subcontinent, which has a large share of population connecting to the main grid in the coming decades (Pillai, 2024). By 2050, we expect 23% of the Indian Subcontinent's transmission grid to be HVDC.

Transmission grid growth can also come in the form of non-new build expansion, primarily through reconductoring and grid enhancing technologies (GETs) like dynamic line ratings (DLR), advanced power flow control, and topology optimization. As explained in DNV's *New Power Systems* report (2024), DLR can expand the North American grid capacity by as much 25% at very little financial cost compared with building new transmission grid lines (DOE, 2024). Similarly, reconductoring – replacing old transmission lines with new and uprated lines – is also a financially feasible, no-regret option in many regions (Mirzapour et al., 2024)

> Grid-enhancing technologies are often no-regret options to increase grid capacity in many regions.

FIGURE 2.8

Transmission grid capacity by type of current in selected regions



Percentages show share of DC. Historical data source: GlobalData (2024), DNV analysis

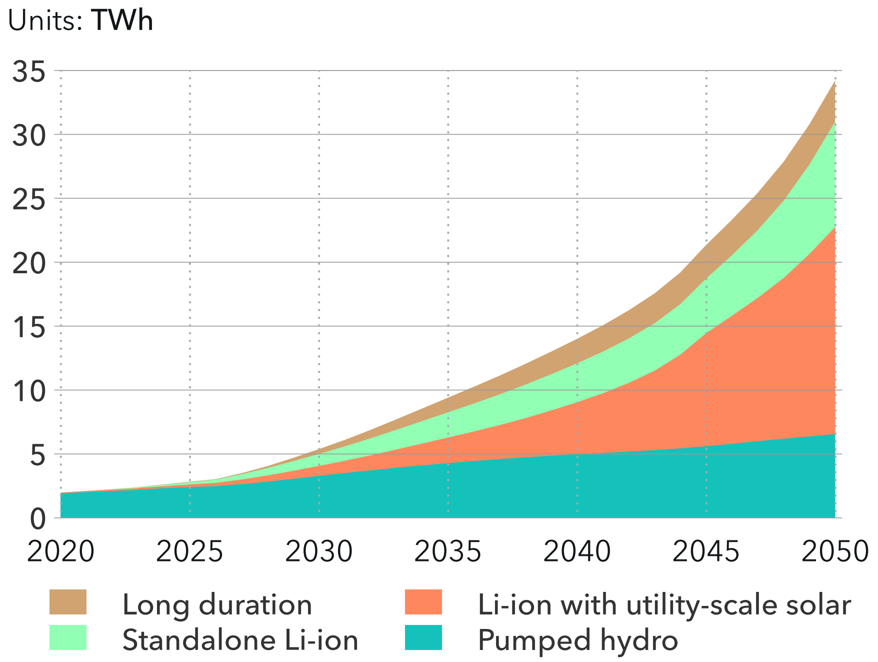
2.3 STORAGE AND FLEXIBILITY

Flexibility and energy storage play critical roles in a power system undergoing significant transformation. Our projected seven-fold increase in renewable power generation will drive a corresponding 17-fold expansion in global utility-scale energy storage capacity, growing from 1.75 TWh in 2023 to 30 TWh by mid-century.

As VRES become more prevalent, the need for flexibility in both supply and demand will become increasingly crucial. By 2050, we project the global demand for flexibility to reach approximately 34% of the average annual power demand. With a doubling of the annual average demand, this corresponds to quadrupling of the flexibility demand. If electrification is the key to decarbonization and the grid is the lock mechanism that allows the key to be used, then storage and flexibility are the plug and tumblers that ensure a seamless unlocking.

FIGURE 2.9

World utility-scale electricity storage capacity



Electricity storage

Electricity storage is crucial for effectively integrating variable renewables into the evolving power grid. It allows for the accumulation of low-cost, excess electricity generated by grid-connected solar and wind power, for discharge to the grid when renewables generation levels are low or absent. In 2023, pumped hydro was the predominant form of utility-scale electricity storage (Figure 2.9). However, geographic limitations and biodiversity concerns will constrain future development of pumped hydro.

Li-ion batteries are already emerging as key players in short-term storage, offering around two hours of storage capacity, although as we explain below that duration is in the process of lengthening. Moreover, they contribute to frequency regulation,

rapid response for balancing supply and demand, and reducing the need for spinning reserves. Our forecast predicts a significant increase in Li-ion battery capacity, reaching 1.7 TWh by 2030 and expanding further to an impressive 24.5 TWh by 2050.

By 2050, we expect the majority of these Li-ion batteries to be co-located with solar power plants, storing inexpensive daytime electricity and discharging it back to the grid during peak demand periods when prices are higher (Figure 2.9).

A shift is underway in major battery storage markets like Greater China, North America, and OECD Pacific. As storage capacity surpasses 0.5% of grid capacity, the focus is transitioning from frequency-response management to broader applications such as price arbitrage or capacity provision.

This shift has led to average storage durations increasing from two to four hours. It also opens up additional revenue streams with the potential to yield significant tail benefits – substantial financial returns for battery storage operators that can exceed their accumulated weekly levelized costs in just a few hours. These changes create disproportionately positive financial outcomes in a relatively short period of operation.

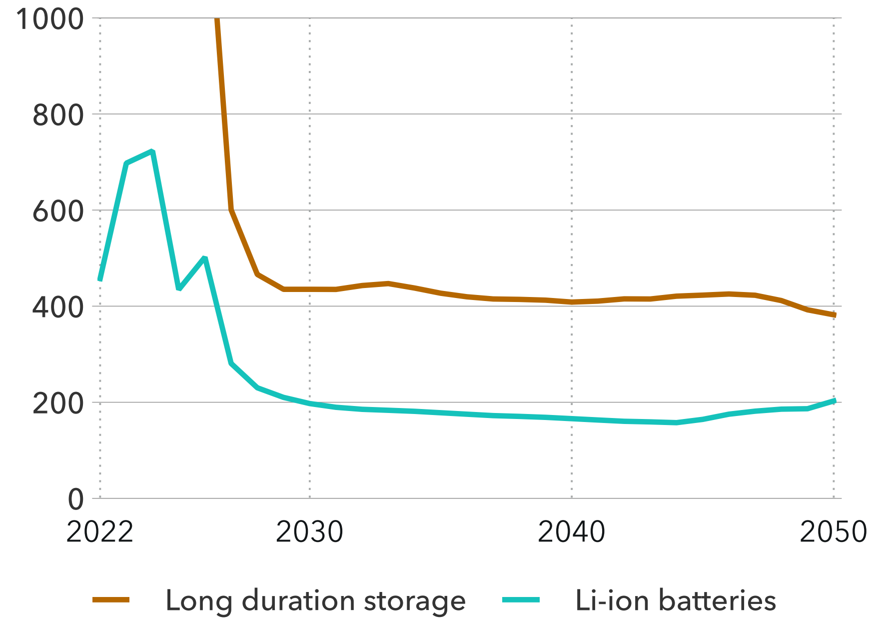
While Li-ion batteries currently dominate the short-duration storage market, there is growing interest in alternative long-duration storage technologies. These technologies – categorized as Long Duration Energy Storage (LDES) – typically offer storage durations ranging from 5 to 24 hours and include innovations such as flow batteries, zinc-based chemistries, and gravity-based storage methods. Our projections suggest that these solutions will enter the mainstream market in the latter half of the 2030s, with a target of achieving 3.2 TWh of long-duration capacity by 2050.

The expansion of both Li-ion batteries and LDES is driven by our global projections of weighted average levelized cost (Figure 2.10). By 2030, we expect utility-scale Li-ion battery system costs to fall below USD 200/MWh and stabilize at this level globally, with even lower costs in markets like North America and Greater China. In contrast, LDES will have higher costs but will offer longer storage durations not achievable by Li-ion batteries. Our forecast, supported by historical modelling, highlights the potential of LDES – particularly vanadium flow batteries – which show promising techno-economic prospects for 8- to 24-hour applications and could present cost advantages over Li-ion systems (Poli et al., 2024).

FIGURE 2.10

Levelized cost of Li-ion batteries and long duration energy storage

Units: USD/MWh



Emerging 'very-long duration' technologies also suggest significant future cost efficiencies. While their commercial viability is still under evaluation and they are not included in this report, their development could potentially reshape the energy storage landscape.

Despite Li-ion batteries currently dominating the market at 95% of new storage projects, there are short-term uncertainties surrounding their future. Post-pandemic supply chain challenges have driven up Li-ion battery prices in some regions. Additionally, tariffs imposed by regions like North America on Li-ion batteries imported from areas with production overcapacity, particularly Greater China, could lead to further price increases in the North American market (Murray, 2024). While these tariffs aim to incentivize local production and protect regional interests, they may temporarily raise costs for project developers.

Moreover, short-term volatility in the prices of lithium, nickel, and other critical minerals – stemming from material shortages, processing capacity constraints, and geopolitical conflicts – could drive the development of alternative battery chemistries. This shift may slow the cost reductions typically achieved through 'learning-by-doing' (Figure 2.10).

The true momentum for electricity storage solutions will come from revenue models that value storage services and the increasing adoption of VRES.
We expect demand for these batteries to grow as technology advances and policies evolve. Ultimately, our long-term storage market forecasts depend on potential cost innovations and supportive policy measures, particularly for emerging battery technologies.

Flexibility

Flexibility in a power system is the ability of the electricity grid to respond effectively to changes in supply and demand and ensure a reliable and stable energy supply. It involves the grid's capacity to quickly adjust power generation, consumption, or storage to maintain the balance between electricity supply and demand in real-time. This is especially important as the grid integrates more VRES like wind and solar, which can fluctuate based on weather conditions.

> Short-term uncertainties surrounding Li-ion batteries could temporarily raise their costs for project developers.

In Figure 2.11, we examine the projected increase in the ratio of daily hour-to-hour standard deviations to average load. This helps us to understand how each technology responds to this short-term (hourly) variability. We gauge the flexibility contribution by observing the difference in supply standard deviation with and without a particular technology.

In 2023, almost all of the short-term flexibility need was provided by thermal power plants, about 15% of the average annual electricity demand, globally. This need for flexibility will quadruple by 2050. As thermal power plants give way to non-fossil generation, Li-ion batteries emerge as the primary source of short-term flexibility worldwide – dominating all other sources by 2040. These batteries will either be integrated with renewables or operate as standalone systems.

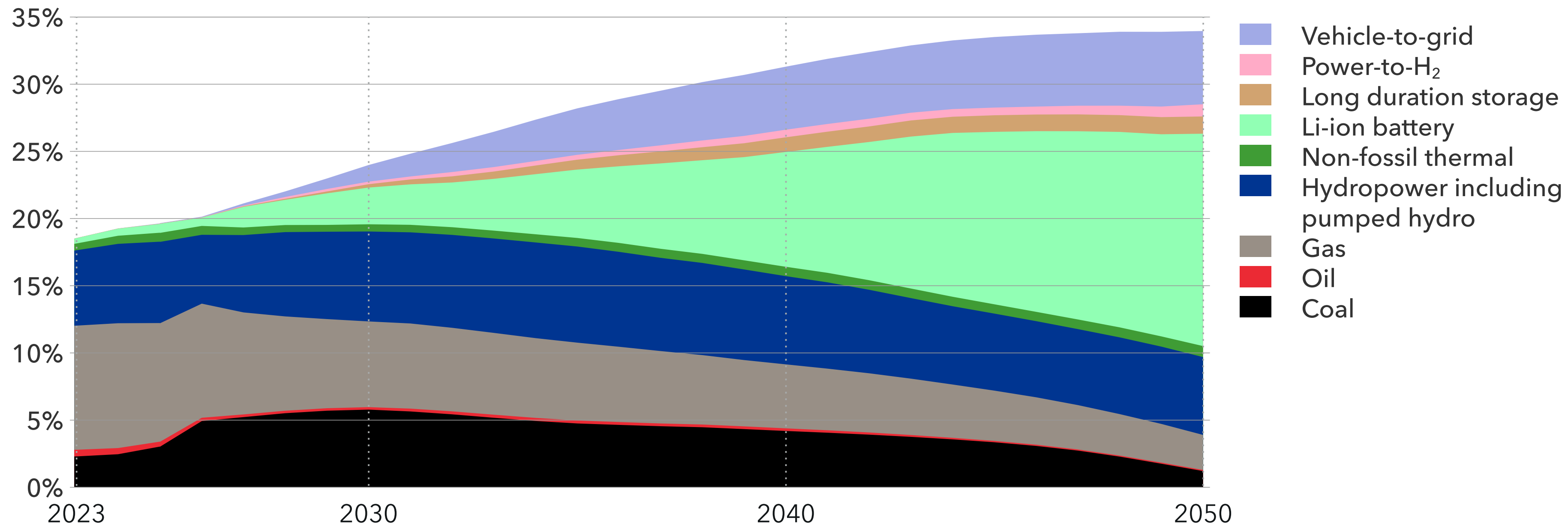
As Li-ion batteries take over, existing thermal plants will increasingly operate alongside renewables, amplifying the importance of the flexibility of thermal plants. However, it is essential to note that not all thermal sources have the same ease in ramping their output up or down – an ability that will increasingly determine the economic viability of thermoelectric power.

Vehicle-to-grid (V2G) is an emerging flexibility mechanism that provides about 18% of the global flexibility needs in 2050 (Figure 2.11). V2G, along with other systems like behind-the-meter storage, is part of the burgeoning 'prosumer' trend. EVs deserve special attention in this flexibility narrative. More than just transportation mediums, EVs are evolving into crucial grid components (EVconnect, 2020; see also DNV 2022). This transformation is fuelled by financial stimuli from net metering schemes and incentives for V2G capable charging apparatuses. With these incentives, EV owners could potentially offer stored energy to the grid during high demand, opening a revenue channel that can reduce EV ownership expenses and bolster the embrace of clean energy.

FIGURE 2.11

Global flexibility provided by technology as a fraction of annual average demand

Units: Percentages



Another interesting demand-side flexibility measure is the rise of 'virtual powerplants' (VPP). A VPP is a network of decentralized power-generating units, energy storage systems, and flexible energy consumers that are coordinated through advanced software to operate as a unified and flexible power plant. Unlike traditional power plants that rely on a single, large-scale facility, a VPP aggregates various small-scale resources – such as rooftop solar panels, wind turbines, battery storage systems, and demand response programmes – to create a reliable and efficient energy supply (DOE, 2022).

The transition to greater flexibility is not just about new equipment. It demands modifications like retrofitting specific parts and significant investment in automation and analytics. Improving the accuracy of renewable power generation predictions and refining demand responses will be instrumental in handling surpluses in renewables and in reallocating electricity usage from high-demand periods to lower demand ones.

Moreover, there is a pressing need for innovative market structures. These should promote the adaptive functioning of thermal plants and introduce fresh contract models, alterations in grid codes, and new benchmarks. From a broader system perspective, we are witnessing the rise of smart grid features. The integration of tools like smart meters, Internet of Things (IoT) sensors, and advanced automation techniques promises more efficient energy flow management. Furthermore, flexibility tools – such as VPP – give consumers the ability to change behaviour based on economic stimuli.

Lastly, another avenue of flexibility emerges from converting VRES into other energy forms like hydrogen. Strengthening physical transmission systems and refining the connection between power generation and consumption hubs will further optimize the renewable power supply's utility. While power-to-hydrogen plays a small role in providing flexibility globally, in some regions such as North America, grid-connected electrolysers are set to play a key balancing and flexibility role. For further analysis of grid-connected electrolyser's potential role in the power system, see DNV's *New Power Systems* report (DNV, 2024).

2.4 HYDROGEN

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 – ammonia, e-methanol, and other e-fuels – need to account for about 15% of the world's energy demand by 2050 (DNV, 2023). However, our projections show that the forecast global uptake of hydrogen falls very short of these goals; we expect hydrogen and its derivatives to comprise only 0.25% of the global final energy mix by 2030 and 4% by 2050.

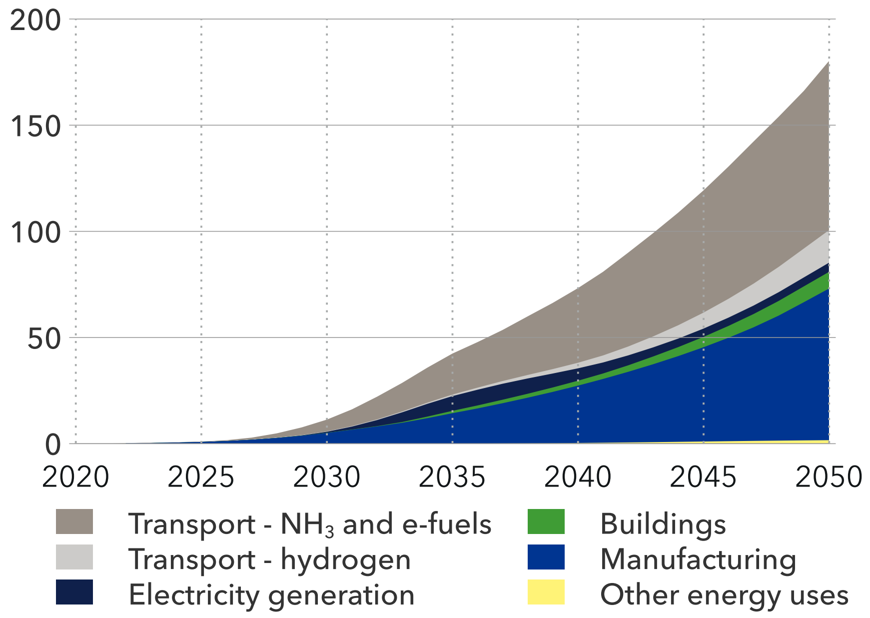
High-income regions are pioneers in driving hydrogen energy-related technology developments and uptake through energy and industrial policies. Their policy frameworks have seen ongoing refinement, and announcements on government funding are numerous with distinct emissions intensity prerequisites for public support.

In the EU, the two *Delegated Acts* (adopted in June 2023) include requirements for renewable fuels of non-biological origin (RFNBO) to qualify as renewable hydrogen (under the *Renewable Energy Directive*), programmes providing EU funding for infrastructure-related projects, and the conclusion of the European Hydrogen Bank's first auction during spring 2024. In North America, the US's *Inflation Reduction Act* and *Infrastructure Investment and Jobs Act* and Canada’s *Clean Hydrogen Investment Tax Credit* provide ongoing incentives for clean hydrogen production and related infrastructure. Similarly, in the OECD Pacific region, Japan and South Korea are establishing CfD schemes for production and imports during 2024.

FIGURE 2.12

World demand for hydrogen and its derivatives as energy carrier by sector

Units: MtH$_2$/yr



All non-transport uses are pure hydrogen.

These policy developments are leading to a growing number of projects in the respective regions and a relatively rapid increase in hydrogen adoption towards and beyond 2030 (Figure 2.12). As a result, we expect Europe, North America, and the OECD Pacific to achieve significantly higher shares of hydrogen and its derivatives in their final energy mixes – around 7% each by 2050 – positioning them as frontrunners in hydrogen use.

Although we expect hydrogen and its derivatives to account for less than 4% of global energy demand in 2050, the advancements in hydrogen technology and infrastructure over the next three decades will be substantial. This represents the emergence of an entirely new energy source that will power one-twentieth (and growing) of the world's energy needs. These developments have the potential to transform various industries. We estimate the global expenditure (including capital and operational expenditures) on hydrogen production for energy purposes from now until 2050 to reach USD 6.8trn, with an additional USD 180bn allocated for hydrogen pipelines and USD 530bn for the construction and operation of ammonia terminals.

2.4.1 Hydrogen demand

Hydrogen's future demand as an energy carrier will grow from its current negligible levels to surpass 188 MtH_2 annually by the year 2050. This is a sharp upward incline (Figure 2.13), but as explained above, not nearly sharp enough to meet the *Paris Agreement* transition outcome. The predominant application of hydrogen will be in manufacturing (73%), followed by transport (14%), and buildings (7%), with the remaining portion allocated for electricity generation and various other purposes.

Transport

Maritime: Hydrogen derivatives will play a crucial role in decarbonizing international shipping. Since January 2024, the EU's emissions trading system (ETS) covers CO_2 emissions from all large ships, with surrender of allowances for 100% of reported emissions from 2027 onwards. In 2025, *FuelEU Maritime* will impose a well-to-wake GHG intensity requirement, effectively forcing the use of qualified low GHG fuels. The International Maritime Organization (IMO) is currently working on measures to achieve the GHG strategy aiming for shipping to reduce total GHG emissions at least by 20% in 2030, by 70% in 2040 (all relative to 2008) and net-zero GHG emissions by or around 2050. For further details refer to DNV's *Maritime Forecast to 2050* (2024).

Electrification will only be viable for onshore power when ships are docked and for short-distance sea travel – such as near-shore ferry operations – so we expect hydrogen-based fuels like ammonia and e-fuels to dominate zero-emission fuels for the shipping industry by 2050. Our forecast for hydrogen adoption suggests that e-fuels, primarily e-methanol, will make up 500 PJ or 3% of the shipping fuel mix by 2030, increasing to 1,270 PJ (9%) by 2040, and reaching 1,650 PJ (12%) by 2050.

Like e-methanol, ammonia can leverage much of the existing infrastructure, although it comes with higher production costs than current alternatives. Capturing CO_2 during ammonia production from natural gas is relatively straightforward, making low-carbon ammonia the leading option for shipping in our forecast. We expect the toxicity concerns with ammonia to be addressed, allowing for large-scale transport from cost-effective production regions to global bunkering hubs. Although we project ammonia to have a slower initial uptake in shipping than e-methanol, it is likely to accelerate more rapidly toward the end of the forecast period, especially since biogenic CO_2 for e-methanol will be hard to source. We forecast ammonia usage in shipping to reach 170 PJ (1% of the shipping fuel mix) by 2030, 1,900 PJ (13%) by 2040, and 5,000 PJ (36%) by 2050. While our forecast uptakes of e-fuel and ammonia are considerable, it falls short of what is needed to reach the IMO strategy (see the discussion of maritime transport in Section 1.1 for further details).

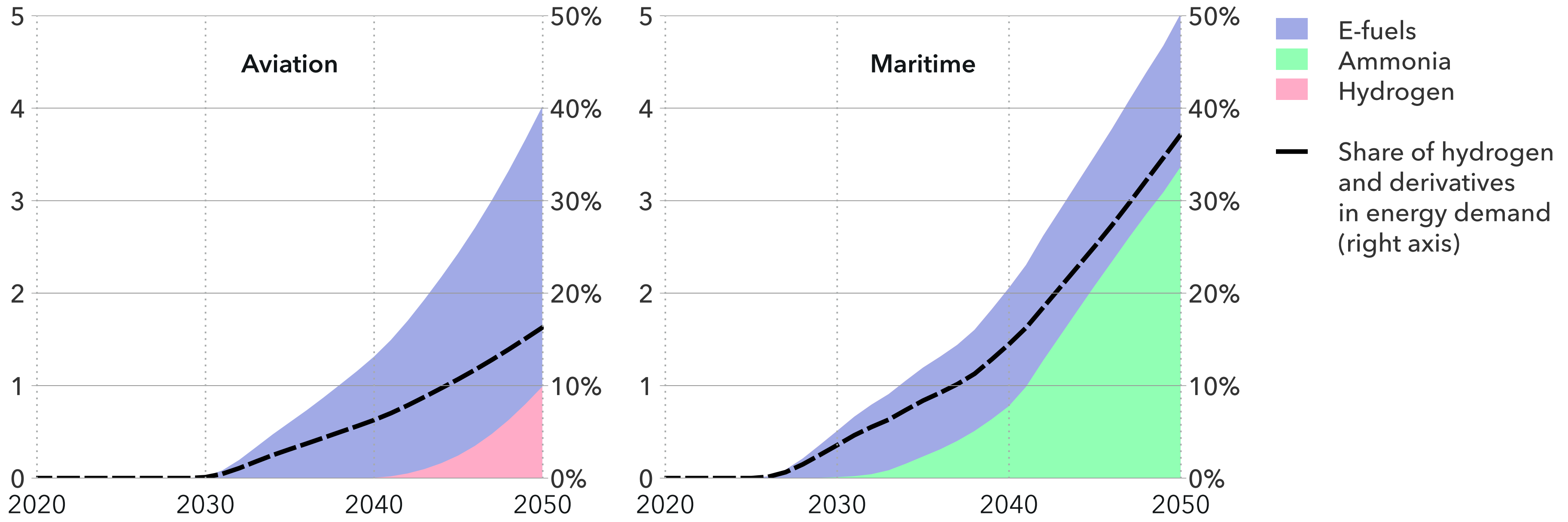
Despite ammonia itself being carbon-free, nitrogen oxide (NO_x) emissions can be an issue when combusting ammonia as a fuel in maritime applications. However, NO_x emissions can be effectively managed through appropriate technology and engine design.

Aviation: We expect hydrogen, as e-fuels, to gain momentum in aviation during the 2030s. This will be driven largely by cost and availability factors, but also by a market ramp-up for non-conventional fuels created by policy mandates like the EUs *Renewable Energy Directive* (REDIII) and *RefuelEU Aviation* initiative's binding 2030 targets for renewables in transport energy use, sustainable aviation fuels,

FIGURE 2.13

World aviation and maritime subsectors demand for hydrogen and derivatives

Units: EJ/yr (left); Percentages (right)



and minimum shares for synthetic fuels. However, e-fuels are about four to five times more expensive than fossil kerosene, so the widespread adoption of e-fuels will depend on a significant increase in renewable electricity production to bridge the current cost gap.

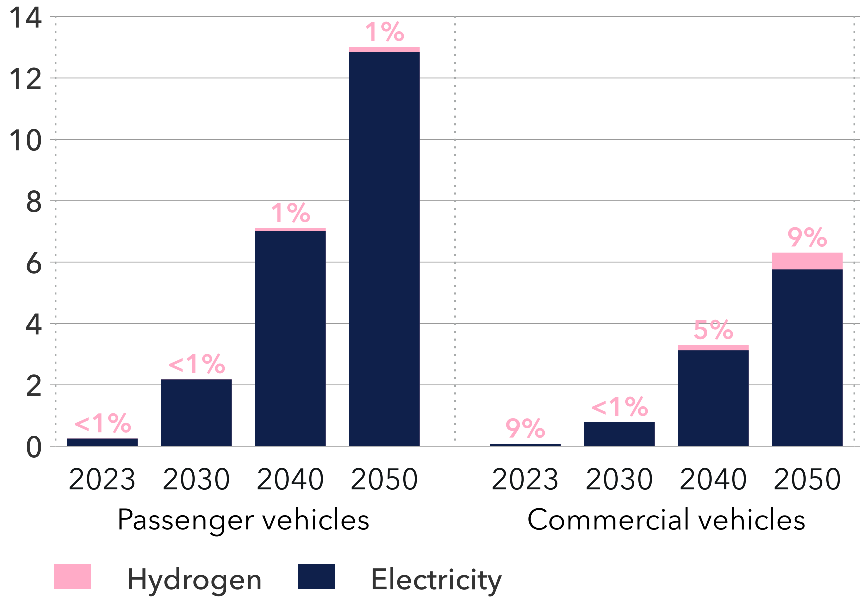
In aviation, we expect e-fuels to surpass pure hydrogen by a three-to-one margin, making up 12% of the fuel mix by 2050. This is largely due to e-fuels being compatible with all types of flights as drop-in replacements. In contrast, pure hydrogen is mainly suited for short to medium-haul flights because of its lower energy density and the need for extensive storage which requires aircraft designs with higher per-passenger costs. In the long term, liquid hydrogen may be used for longer-haul jet turbines, but the fuselage must be redesigned to make space for the added volume of hydrogen. Altogether, we project pure hydrogen and hydrogen-based e-fuels to account for approximately 16% of aviation energy use by 2050.

Road transport: In road transport, fuel cell electric vehicles (FCEVs) are significantly less efficient, more complex, and therefore more costly than battery electric vehicles (BEVs). As a result, automakers are focusing exclusively on developing BEV models for passenger vehicles to achieve zero-emission transportation. We expect this emphasis on BEVs to lead to BEVs capturing a dominant 97% share of new passenger vehicle sales globally by 2050, while FCEVs will account for just 0.2% of new vehicle sales. Hitherto, hydrogen has been the leading contender for decarbonizing heavy trucking. However, current trends suggest that battery-electric solutions will also make significant inroads in this segment. As a result, hydrogen is likely to play a relatively minor role in road transport despite truck and engine manufacturers having developed combustion engines which may use hydrogen. By mid-century, we expect hydrogen to meet only about 1% of road transport energy demand, slightly less than biomass and natural gas. This usage – largely concentrated in heavy-duty and long-haul trucking where hydrogen may be used as range extension as all FCEVs and BEVs have electric motors – translates to approximately 710 PJ in 2050, or about 5.9 MtH_2 per year (Figure 2.14). Notably, around 59% of this demand will be in North America, driven by its large vehicle fleet and strong policy focus on decarbonizing transportation. We expect the OECD Pacific region to account for 21% of this demand, with Europe contributing another 16%.

FIGURE 2.14

Road sector EV energy demand

Units: EJ/yr



Percentage show share of hydrogen in EV energy demand.

Manufacturing

Hydrogen has the potential to replace fossil fuels in generating high-temperature heat in industrial processes. However, the current utilization of hydrogen in these high-heat applications is minimal. This is primarily due to hydrogen's costliness as an alternative fuel which makes it less competitive than traditional fossil-fuel technologies. Additionally, hydrogen faces tough competition from bioenergy, particularly in scenarios with higher carbon prices. Competition is also emerging from technical advances in the electrification of industrial heat, specifically in electrothermal energy storage (Systemiq, 2024).

Nonetheless, we anticipate renewable and low-carbon hydrogen to play a significant role in the manufacturing sector by 2050, particularly in regions leading the transition, such as Greater China (27% of hydrogen demand in the sector), North America (25%), and Europe (15%). According to our forecast, the demand for hydrogen as an energy carrier in manufacturing will experience gradual growth, reaching nearly 8.6 EJ/yr (approximately 71 MtH_2/yr) by 2050 (Figure 2.15). This accounts for about 5% 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 4.2 EJ/yr (49% of the total). This is in addition to the non-energy use of hydrogen in the direct reduction of iron, which will be approximately 1 EJ/yr, equivalent to around 8.1 MtH_2/yr.

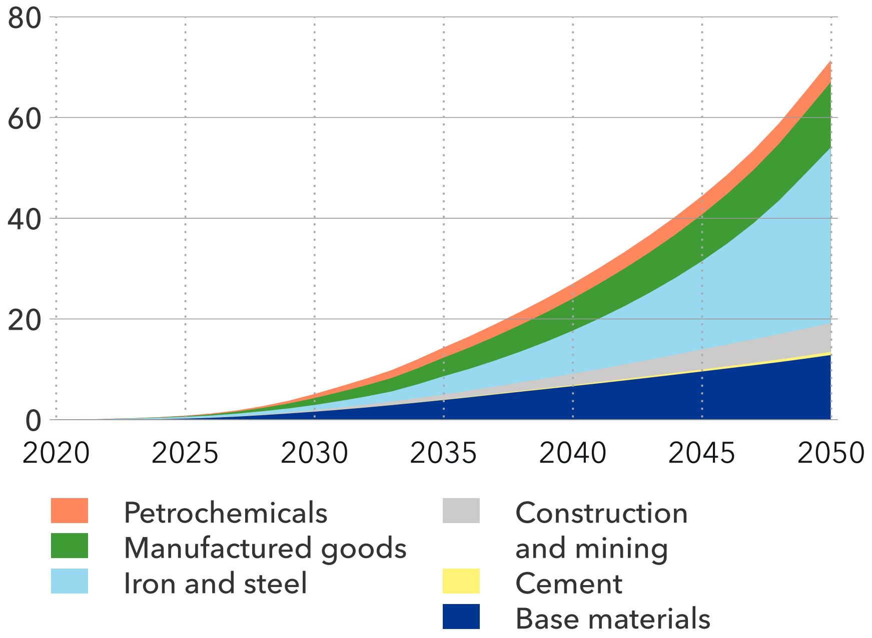
Buildings

In our analysis, we project hydrogen uptake in buildings to reach approximately 0.9 EJ/yr (about 7.8 MtH_2/yr) by 2050. This constitutes only a modest 0.6% of the total energy demand in the buildings sector. Most of this demand will be space heating (50%) and water heating (41%). This share of hydrogen remains tiny compared with natural gas, which is expected to fulfil about a fourth of the energy demand in buildings by 2050.

FIGURE 2.15

World hydrogen demand in manufacturing by subsector

Units: MtH_2/yr



The limited expected uptake of hydrogen in the buildings sector can be attributed to various factors including comparative efficiency, cost considerations, safety considerations, and the availability of infrastructure compared with competing technologies like electric heat pumps and district heating systems.

We anticipate the hydrogen utilization in buildings to be concentrated in Europe, North America, and the OECD Pacific. These regions are characterized by the presence of existing natural gas infrastructure and relatively more accessible hydrogen sources.

Power and seasonal storage
In regions with a significant share of solar and wind, hydrogen is a practical option for managing peak demand and storing surplus electricity for long periods. However, this method involves considerable energy losses and substantial storage needs.

When considering the hierarchy of hydrogen applications, using hydrogen for re-electrification will be a lower priority. Starting around 2030, we anticipate a gradual introduction of hydrogen into power generation, initially through blending it with natural gas. Over time, the role of hydrogen in power generation will grow, driven by the need to manage peak demand.

We forecast the OECD Pacific region to be at the forefront of this transition, followed by Europe and Greater China. North America will begin participating by the mid-2040s. By the middle of the century, these regions will collectively use nearly 10 MtH_2/yr for electricity generation.

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 slight demand decreases in respective sectors, there will be an increasing need for hydrogen derivatives used in energy applications. By 2050, we expect the demand for hydrogen to produce e-fuels and as a fuel source for ammonia to surpass the combined demand for hydrogen in oil refining and fertilizer production.

As we approach 2050, the use of traditional CO_2-intensive production methods for feedstock hydrogen – such as methane reforming and coal gasification – will decline. These processes will be gradually replaced by more sustainable alternatives, including methane reforming with carbon capture and storage (CCS), grid-connected electrolysis, and electrolysis powered by dedicated renewable energy sources. More specifically, some 19% of ammonia produced for fertilizer will come from renewable hydrogen and around the same from low-carbon hydrogen (mostly methane reforming with CCS).

> 81% of the world's hydrogen will come from low-carbon and renewables-based methods.

2.4.2 Hydrogen supply

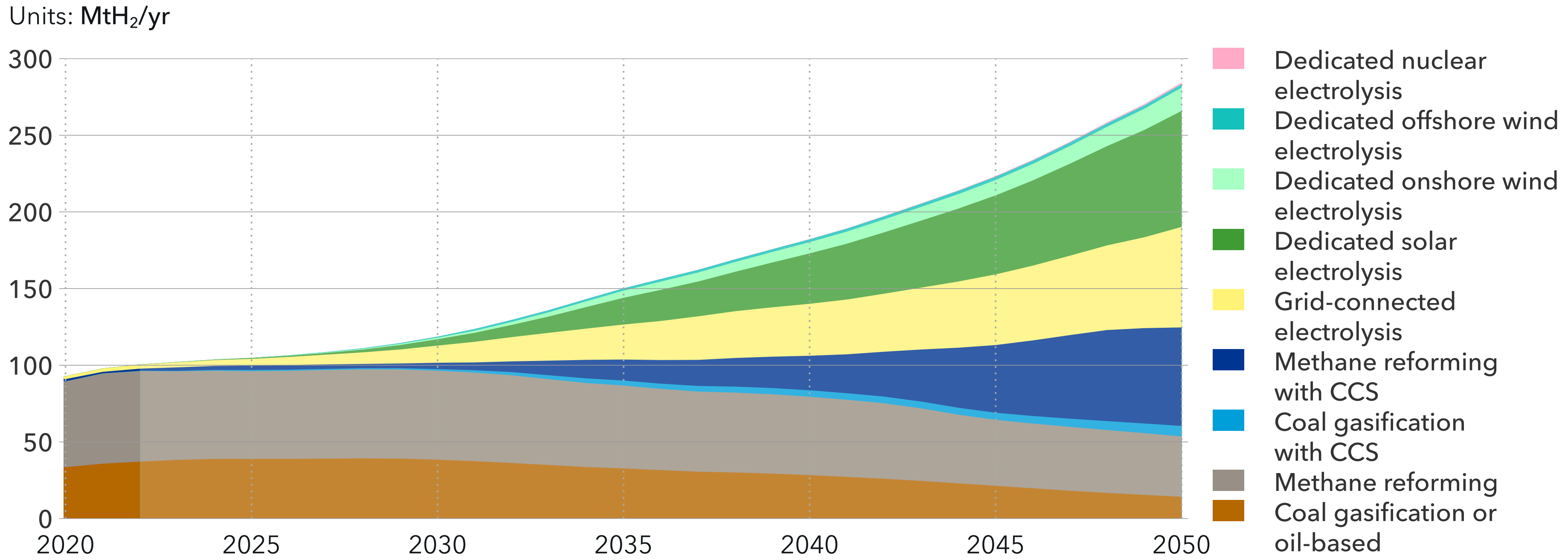
The future composition of hydrogen supply will be shaped by two intertwined trends: the growing role for hydrogen as an energy carrier and the greening of hydrogen production methods. Since the primary aim of incorporating hydrogen into energy systems is reducing carbon emissions in areas where electrification is not feasible, attention to the lifecycle emission-intensity levels of production methods will become dominant.

By 2030, our projections show that 20% of the global hydrogen supply will come from low-carbon and renewable sources. Specifically, methane reforming with CCS will make up 14% of the global supply, while hydrogen produced through electrolysis will account for 4%. By 2050, the picture will have altered fundamentally. An impressive 81% of the world's hydrogen will come from low-carbon and renewables-based methods. This will include 23% from methane reforming with CCS, 24% from grid-connected electrolysis, 27% from solar-powered electrolysis, 6% from wind-powered electrolysis, and 0.5% from nuclear-powered electrolysis (Figure 2.16).

Low-carbon hydrogen: The primary factors influencing the share of different production methods in the hydrogen supply mix are cost and the speed of implementation. Currently, the most

FIGURE 2.16

World hydrogen production by production route



Historical data source: IEA Future of Hydrogen (2019), IEA Global Hydrogen Review (2021)
Does not include hydrogen use in residual form from industrial processes.

economical low-carbon hydrogen production method is methane reforming with CCS, known as blue hydrogen, which costs just under USD 3/kgH_2 on average (assuming 90% capture rate). This cost mainly reflects regions like North America and North East Eurasia where natural gas is cheaper. However, since 2020, higher gas prices have increased blue hydrogen costs by 20% to 30% in gas-producing areas and by 60% to 400% in gas-importing regions.

Despite a projected decrease in gas prices by the 2030s, low-carbon hydrogen faces additional challenges. CCS technology is still developing and issues such as long-term storage, cost uncertainties, and limited economies of scale impede its rapid deployment. Furthermore, achieving CO_2 capture rates above 90% remains economically unviable, making low-carbon hydrogen less competitive against renewables-based production routes in the medium-to-long term. Nevertheless, as the costs of methane reforming and carbon capture decrease and carbon prices rise, low-carbon hydrogen is expected to gain a significant market share, particularly in ammonia and methanol production. By 2050, we project 64 MtH_2/yr from methane reforming with CCS to account for 23% of the global hydrogen supply.

> Long-term storage, cost uncertainties, and limited economies of scale are impeding the rapid deployment of CCS.

Renewable hydrogen: Hydrogen produced through dedicated renewables-based electrolysis currently averages USD 5/kgH_2. This is too expensive relative to unabated fossil-based production routes. However, we expect costs to fall significantly by 2030, with solar or wind-based electrolysis costing around USD 3/kgH_2. The costs will decline further for those production routes towards around USD 2/kgH_2 on average by 2050, with some projects coming in at under one dollar per kgH_2. This decrease will be driven by a 40% reduction in solar panel costs and a 27% reduction in turbine costs, along with improvements in technology. This will lead to a 10% to 30% increase in annual operating hours, depending on the technology and region. Additionally, we project capital costs for electrolysers to drop by 25% to 30% due to reduced financial risk perceptions.

The main cost component of grid-connected electrolysers is electricity; the availability of affordable electricity is of utmost importance. VRES in power systems will significantly affect these electricity prices, with higher VRES integration leading to more hours of very cheap or even free electricity. However, VRES penetration will not be sufficient to significantly impact electricity prices before 2030. Thus, cost reductions in grid-connected electrolysers in the near term will largely come from falling capital costs and government support.

It should be emphasized that our frontrunner regions in hydrogen support – Europe, North America, and the OECD Pacific – are setting requirements on electricity and emissions intensity. Japan has distinct low-carbon hydrogen and ammonia standards and South Korea's links support levels to it clean hydrogen definition with four grades of emissions-intensity based limits. In the US and Canada, tax credits are tiered to a lifecycle GHG emissions range, and the EU requires RFNBO to deliver GHG emissions savings of 70% compared to conventional fossil-fuel based hydrogen.

The EU and US regulatory frameworks also stipulate clear requirements for electrolysis-based hydrogen production that rely on grid-based electricity. For example, starting on 1 January 2028, the EU will require 'additionality' – renewable electricity powering hydrogen production must come from new capacity that would not exist in the absence of hydrogen/RFNBO production. Prior to this, renewable electricity will need documentation (e.g. a PPA) but can rely on existing renewable generation. In addition, both the EU and the US will begin to apply 'temporal matching' – future hourly matching of renewable electricity and hydrogen production – starting in 2030 and 2028, respectively. These policy requirements aim to ensure that renewable-based electricity consumed by electrolysers comes in addition to renewables meeting renewable electricity consumption targets.

By 2050, two main factors will influence annual operating hours of electrolysers: increased competition from other hydrogen production methods and more hours of low-cost electricity due to higher VRES integration. As VRES becomes more widespread, the number of hours when hydrogen produced from electricity is cheaper than low-carbon hydrogen will increase. Consequently, we expect grid-connected renewable hydrogen to achieve a market share comparable to that of low-carbon hydrogen, with about 160 MtH_2/yr – 56% of the global hydrogen supply – coming from dedicated renewables by mid-century.

Hydrogen transport

Hydrogen will primarily be transported via pipelines for medium distances within and between countries, but it is unlikely to be transported between continents. Ammonia, on the other hand, is safer and more convenient for transport – especially by ship. Therefore 66% of this energy carrier globally will be transported

(Figure 2.17). To maximize cost-efficiency, over 50% of hydrogen pipelines worldwide will be repurposed from existing natural gas pipelines, potentially rising to as much as 80% in specific regions, as we project the cost of repurposing pipelines to be only 10% to 35% of the cost of building new ones.

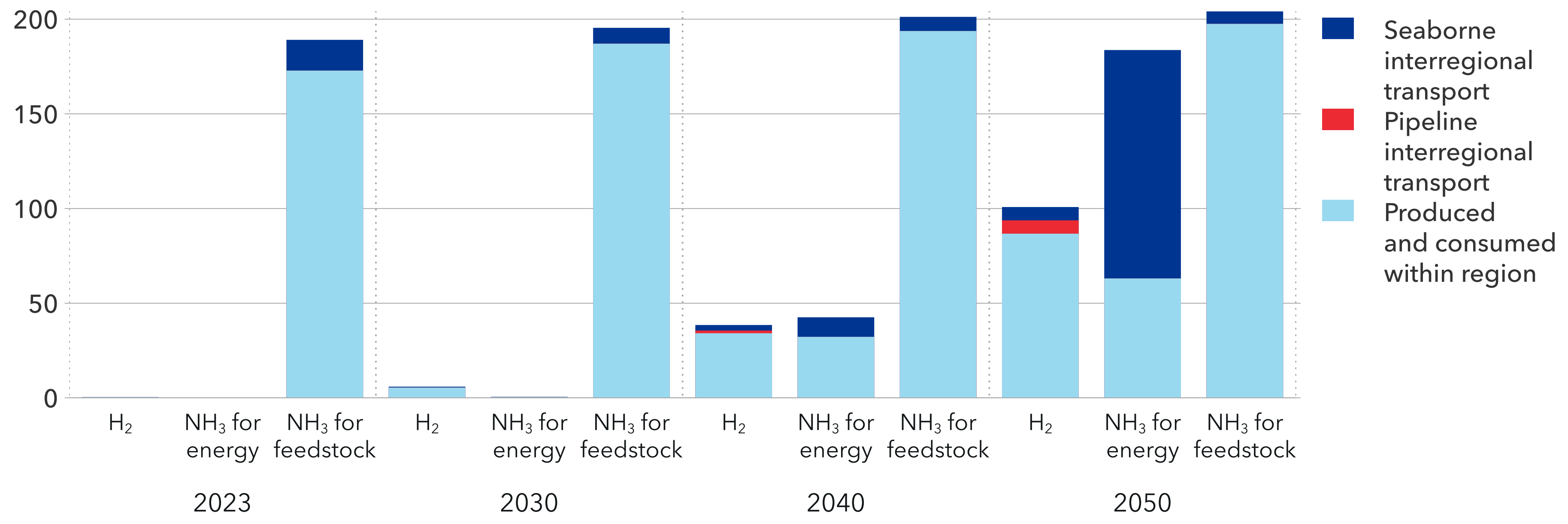
Pure hydrogen transport between regions will play a relatively minor role. Pipeline transportation is the most cost-effective for large volumes and medium distances. For shorter distances and smaller volumes, methods like trucking and rail, typically using ammonia as the carrier, become more practical. Seaborne transport is a viable alternative for longer distances, but it requires energy-intensive and costly liquefaction at the export site and expensive regasification at import locations. This adds USD 1.5/kgH_2 to 2/kgH_2 to costs. By 2050, about 7% of global hydrogen will be transported via ships and another 7% through interregional pipelines.

In our forecast, ammonia emerges as the preferred zero-emission fuel for international shipping. In this analysis, we assume that all seaborne hydrogen transport will involve liquid ammonia; e-methanol is less likely due to availability constraints for biogenic CO_2 and higher production costs. We anticipate a fifteen-fold increase in ammonia seaborne transport from 2030 to 2050. This usage will grow from almost nothing in the mid-2030s to constituting 90% of the trade in 2050, a total of 120 million tonnes of shipments at that time.

FIGURE 2.17

Transport of hydrogen and ammonia

Units: Mt/yr



All numbers displayed in mass terms: Mt of H_2 or Mt of NH_3. The mass of ammonia converted from H_2 is approx. 5-6 times the mass of H_2.

Hydrogen will primarily be transported via pipelines for medium distances within and between countries. In 2021, DNV initiated a joint industry project (JIP) to develop a recommended practice (RP) for hydrogen pipeline systems. The JIP, dubbed H2Pipe, has attracted participation from more than two dozen major industry players and is now in Phase 2, running from 2023 to 2025. This involves comprehensive experimental testing and risk assessments, with the goal of publishing a public RP by 2025.

Headwinds for hydrogen

For the past couple of years we, as forecasters, have become accustomed to saying that hydrogen will cover only 5% of final energy demand by 2050. A *Paris Agreement* transition would require that percentage to be at least 15%. However, spiralling costs across many of the first hydrogen-for-energy projects, and an absence of policies that subsidize hydrogen at the hefty level required for a fast ramp up have led us to revise down our forecast uptake of hydrogen by 2050.

In 2022, our *Energy Transition Outlook* projected that hydrogen production and its derivatives for energy purposes would reach 235 MtH_2 annually by 2050. In our subsequent outlook, *ETO 2023*, we updated this forecast slightly upward to 238 MtH_2 annually, representing a 5% share of the global final energy mix. However, this year, we have revised our mid-century hydrogen forecast downward by 21% from last year's estimate. We now anticipate only 188 MtH_2 for energy purposes annually. This corresponds to a 3.9% share of hydrogen in the global energy mix. We have also revised our short-term forecast downward, decreasing our expectation of hydrogen's share within the energy mix from 0.4% to 0.2% in 2030 and from 2.6% to 1.5% in 2040.

Several countries and regions have set ambitious hydrogen production targets for the coming years. The EU aims to produce 10 million tonnes of renewable hydrogen annually by 2030, with plans to import an additional 10 million tonnes. Similarly, the US has set a target of 10 million tonnes by 2030 and aims to reach 50 million tonnes annually by 2050. The UK is targeting 10 GW of low-carbon hydrogen production capacity by 2030, potentially translating to 1.5 million tonnes per year. India has set a goal of 5 million tonnes per year by 2030. In the OECD Pacific region, Japan plans to have 3 million tonnes of hydrogen available annually, including through imports, while South Korea aims for annual production of 2.1 million tonnes by 2030.

There are concerns about whether these ambitious targets will be achieved. According to the IEA's Hydrogen Production Projects Database (IEA, 2023), while the number of project announcements is increasing, only 5% of projects aimed at producing renewable or low-carbon hydrogen have reached a final investment decision. The remaining 95% are still in feasibility study or early concept phases. Several high-profile projects have been either cancelled or delayed in 2024. For example, Danish offshore wind developer Ørsted has scrapped its FlagshipONE project in Sweden, which was set to produce up to 55,000 tonnes of e-methanol annually, due to a sluggish market and uncertainties over long-term contracts. Norwegian power producer Statkraft has scaled back its renewable hydrogen capacity ambitions from 2 GW by 2030 to 1 to 2 GW by 2035 citing higher-than-expected costs. Similarly, French energy company Engie has postponed its 4 GW green hydrogen target by five years owing to slow demand development.

Despite the national strategies and policies aimed at supporting hydrogen uptake, implementation delays and insufficient demand-creation policies are hindering progress. Hydrogen remains an expensive option: even when the technology is ready for use, potential buyers are understandably hesitant to pay the higher costs associated with hydrogen as a fuel. At current costs that often exceed USD 5/kgH_2, hydrogen is up to 5 times more expensive per megawatt than natural gas in Europe. Although we expect costs to fall substantially in the next five years to USD 3/kgH_2, hydrogen uptake will be muted in the absence of higher carbon prices and/or subsidies. The chicken-and-egg conundrum is that to get to the more viable USD 2/kgH_2 level (or even around USD 1/kgH_2 for selected projects) that we project for the 2040s, hydrogen needs to progress through a learning curve that only eventuates from mass installation. While we do see substantial buildout of both blue and green hydrogen production in the 2030s, the risk for hydrogen is that policy uncertainty will drive the market to explore other opportunities to tackle hard-to-electrify sectors. Uncertainty will also severely limit the application of hydrogen where direct electrification is possible, even in cases where that requires substantial investment in, for example, retrofitting heat pumps, or installing new electrothermal energy storage technology. The risk of substitution applies even to demand subsectors – like heavy trucking – previously considered a natural domain for hydrogen: at present, we see far more electric options available for trucks than hydrogen alternatives. Finally, few authorities are mandating hydrogen use, which could serve as a viable alternative when the market is not fully prepared.

In July 2024, the European Court of Auditors reported that while the European Commission has made some progress in creating favourable conditions for the hydrogen market, the EU is unlikely to meet its 2030 production and import targets, in part due to the targets being unrealistic (ECA, 2024). According to Hydrogen Europe, a review of national energy and climate plans from 26 EU member states showed that these plans inadequately addressed consumption targets for renewable fuels of non-biological origin (RFNBO) in industry and transport (Hydrogen Europe, 2024). In the US, project developers face uncertainties surrounding tax credit criteria.

On a positive note, there are signs that the initial excitement is giving way to a more pragmatic approach. Although some projects have faced setbacks, others are making significant strides. For instance, the first EU Hydrogen Bank auction, announced on 30 April, allocated nearly USD 780m to seven projects, totalling 1,500 MW of electrolysis capacity. Recent hydrogen support auctions in the UK and Denmark selected 11 projects with a combined capacity of 125 MW and around USD 2.5bn in funding and six projects totalling 280 MW with USD 191m in funding, respectively. In China, large-scale electrolyser projects under construction are expected to add approximately 4 to 5 GW of capacity. Acceptance of 'blue' hydrogen from natural gas is increasing, and we foresee that it will be a part of the hydrogen mix in the coming decades.

> There are signs that the initial excitement is giving way to a more pragmatic approach.

Looking beyond 2030, we expect the continued expansion of wind and solar power to result in substantially lower electricity costs. Those reduced electricity prices, along with decreasing costs for electrolysis equipment and stronger carbon pricing in hard-to-abate sectors, are likely to position hydrogen as a key component of the future energy mix. However, the uptake of hydrogen will be delayed compared with previous forecasts from DNV and others. Some of the slack will be taken up by electrification and energy efficiency measures, but since hydrogen's key application is in hard-to-electrify sectors, the slow-down in uptake is worrying from the perspective of *Paris Agreement* ambitions.

Water requirements

Water is crucial to almost every aspect of energy supply, from fossil fuel extraction and processing to biofuels cultivation and electricity generation. The shift to new low-carbon technologies will change the demand for water but it will remain a key challenge for future low-carbon energy systems.

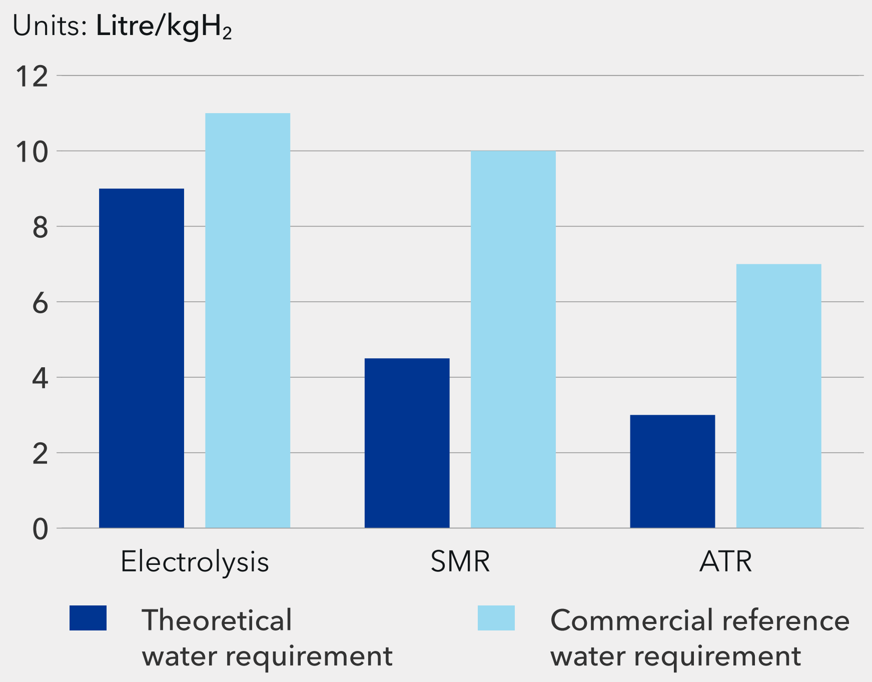
As the share of renewable power in the energy supply increases and replaces coal- and gas-fired power, the demand for cooling water at fossil-fired power stations will correspondingly decrease. Despite this, water demand will remain above current day figures because primary water demand for hydrogen production and secondary water demand for nuclear power cooling will increase over time. If not properly managed, the fuels or technologies used to achieve the energy transition may increase water stress or be limited by it.

Although hydrogen it is the most abundant element on earth, it does not occur naturally. It needs to be either extracted from water (using low-carbon electricity) or refined by reforming fossil-fuel hydrocarbons in the presence of steam. For hydrogen to be a low-carbon fuel, the electricity for electrolysis needs to be low-carbon and CCS needs to be part of reforming fossil fuels.

Water has several roles in the energy transition (Figure 2.19). Primary water is water that is consumed during a process. In thermal generation, this could be the boiler make-up water required for steam cycle heat transfer. Primary water in hydrogen production refers to the breakdown of water molecules into hydrogen and oxygen, with the water involved (9 litres per kg of hydrogen) effectively 'lost'. The chemical reactions that use primary water for hydrogen production are shown Figure 2.19. The actual quantities of water required will be slightly greater than the theoretical values (Figure 2.18) due to process losses and real-world plant inefficiencies.

FIGURE 2.18

Water demand for hydrogen production by technology



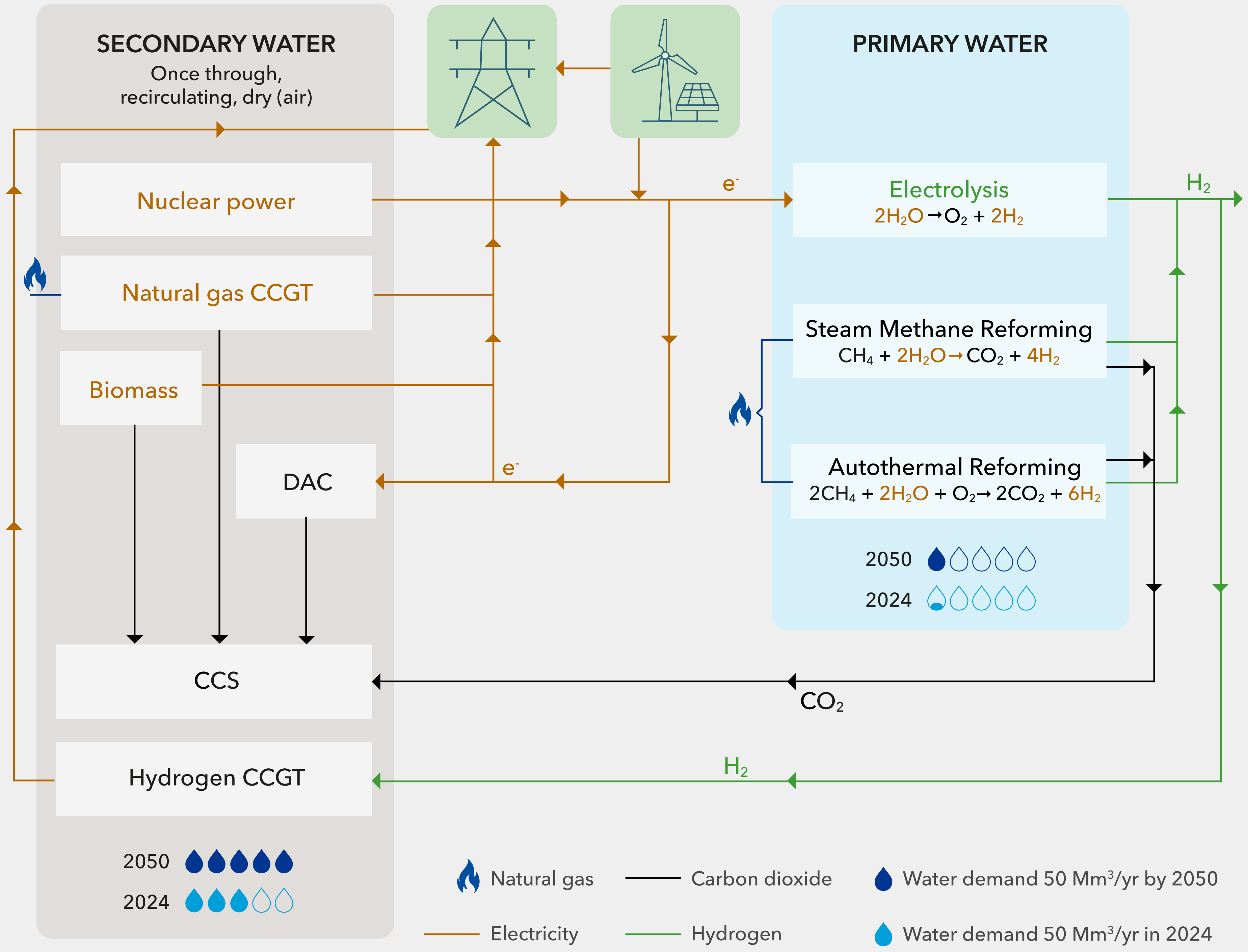
Secondary water – the water required for cooling and might include steam or water injection in the gas turbine or air inlet cooling – is required in all forms of thermal power generation, growing and using biomass, and carbon capture processes. Although secondary water is returned to the environment (e.g. cooling water taken from rivers or the sea and returned), the quantities required are five to ten times greater than primary water. Most importantly, the power generators and CCS plant cannot run without secondary water. One of the most water-intensive processes is bioenergy with CCS (BECCS). Although this does create net negative carbon emissions, a post-combustion CCS plant installed on coal- and gas-fired power plant also decreases the efficiency of electricity production.

Reliable access to usable water sources is a worldwide concern and will affect the feasibility of both hydrogen projects and projects in the wider energy sector. Availability of suitable water resources is already having an impact on energy production and reliability, affecting a wide variety of locations and technologies.

The availability of water resources to supply new hydrogen production will ultimately be contingent on the selected location and scale of production. Identifying and evaluating suitable water supply sources should be a key consideration when deciding the location and design parameters of a hydrogen production plant. However, we stress that when viewed in aggregate terms, the water consumption for hydrogen production will be miniscule fraction of humanity's overall water consumption (Ramirez et al., 2023). Even scaling green hydrogen production to levels aligned with a net-zero pathway to 2050 would not dramatically impact water availability in toto, especially considering that under a 2050 net-zero scenario, the use of water in upstream oil and gas production and thermoelectric plants would dramatically reduce.

FIGURE 2.19

Water in the energy transition



2.5 DIRECT HEAT

Direct heat refers to the thermal energy obtained from power stations and industrial processes and delivered as hot water or steam. This energy is either sold to external entities like district heating systems or used within industries for their operations. Globally, about 20% of households depend on direct heat for space heating, with significant regional variations: 41% in North East Eurasia, 27% in Greater China, and 22% in Europe. Space and water heating in buildings account for 43% of global direct heat use, with the industrial sector consuming an equal share.

The adoption of district heating has varied across regions and time, driven not only by environmental benefits but also by factors like government support, urban density, and available resources. In Scandinavia, strong government backing, and abundant biomass and waste heat have made district heating a key part of urban energy systems. Germany and Eastern Europe are expanding their networks due to policies aimed at reducing carbon emissions. In contrast, regions like the US and Southern Europe face barriers such as lower heat demand, high infrastructure costs, and the dominance of decentralized heating systems.

Regions like North East Eurasia, Europe, and Greater China have historically favoured direct heat (Figure 2.20) due to their centralized planning approaches, which have facilitated the growth of district heating systems. North East Eurasia and Greater China lead global direct heat consumption, followed by Europe, where countries like Germany are prominent. The industrial sector's embrace of direct heat, especially from adjacent power plants, marks a shift towards optimizing energy consumption and reducing carbon footprints, particularly in high-thermal-demand industries like metal smelting and chemical processing.

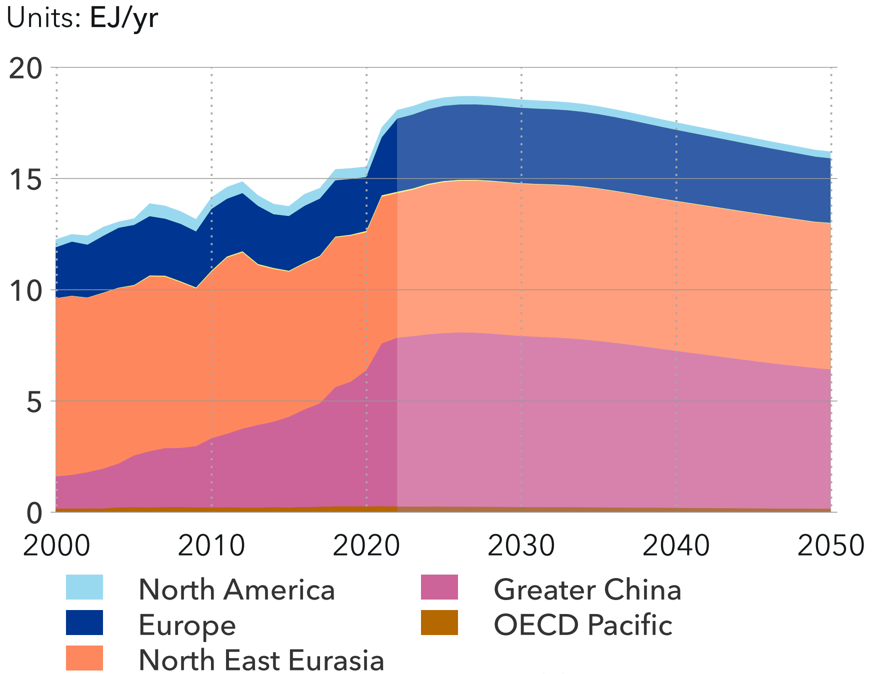
As of 2023, the global direct heat supply was predominantly powered by coal (44%) and gas (42%), with over two-thirds coming from combined heat and power (CHP) plants. However, this energy landscape is evolving (Figure 2.21). By 2030, we expect direct heat demand to see a modest rise to 18.6 EJ/yr before stabilizing and declining to 16 EJ/yr by mid-century, driven by changes in Greater China. The sources of this demand are also shifting, with coal's dominance expected to decrease in favour of bioenergy, particularly from municipal and industrial waste, and natural gas. By 2050, bioenergy and natural gas are projected to provide 47% and 26% of direct heat, respectively, with coal's share falling to 26%.

The future role of district heating and direct heat will be shaped by technological advancements, market dynamics, and regional energy policies. While regions like North East Eurasia, Europe, and Greater China have set certain precedents, each area will navigate its own path based on unique needs and resources. These evolving trends will significantly influence sustainable urban and industrial development in the coming decades.

> Globally, about 20% of households depend on direct heat for space heating.

FIGURE 2.20

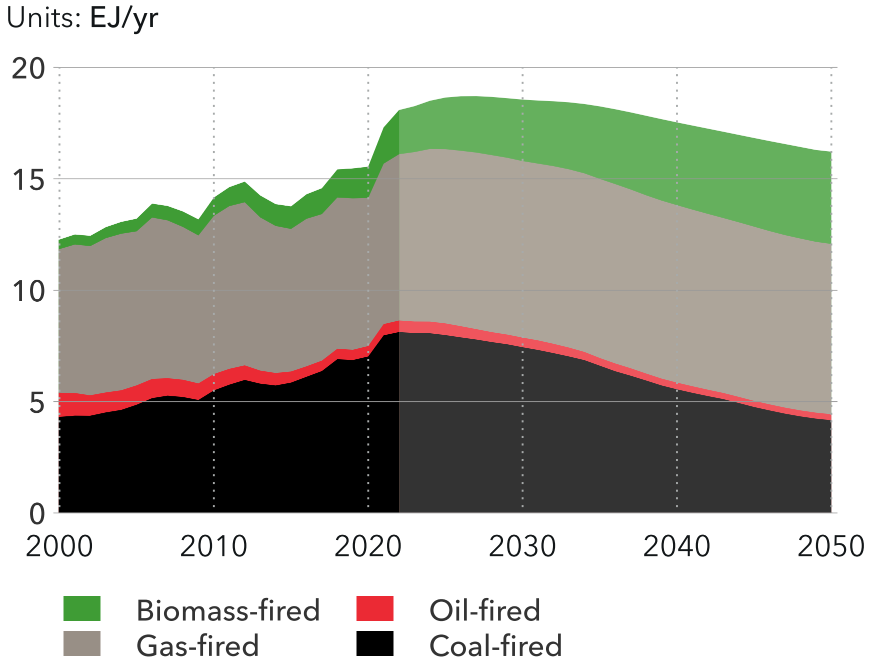
World direct heat demand by region



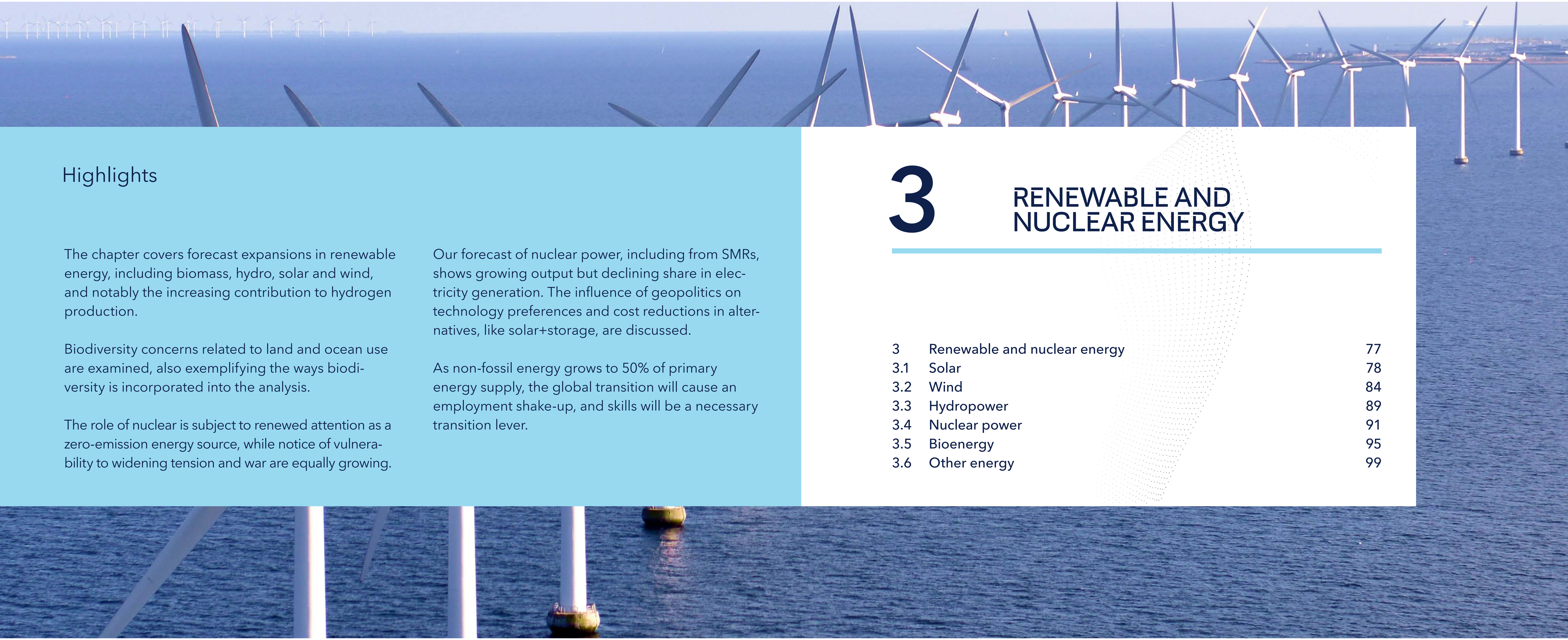
Historical data source: IEA WEB (2024)

FIGURE 2.21

World direct heat supply by power station type



Historical data source: IEA WEB (2024)



3

RENEWABLE AND NUCLEAR ENERGY

Highlights

The chapter covers forecast expansions in renewable energy, including biomass, hydro, solar and wind, and notably the increasing contribution to hydrogen production.

Biodiversity concerns related to land and ocean use are examined, also exemplifying the ways biodiversity is incorporated into the analysis.

The role of nuclear is subject to renewed attention as a zero-emission energy source, while notice of vulnerability to widening tension and war are equally growing.

Our forecast of nuclear power, including from SMRs, shows growing output but declining share in electricity generation. The influence of geopolitics on technology preferences and cost reductions in alternatives, like solar+storage, are discussed.

As non-fossil energy grows to 50% of primary energy supply, the global transition will cause an employment shake-up, and skills will be a necessary transition lever.

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3.6 Other energy 99

3 RENEWABLE AND NUCLEAR ENERGY

Renewable energy is far more than just solar and wind. Bioenergy currently accounts for almost two thirds of renewable energy which in turn makes up 15% of world energy use at present. Within electricity, renewables cover 31% of generation, almost half of which is hydropower. In the coming years, variable solar and wind will grow to dominate and transform electricity generation and the global energy system itself. While nuclear energy is not 'renewable', it is a zero emission and hence covered in this chapter. Nuclear presently covers 9% of electricity and 5% of all energy, with moderate growth going forward.

The growth of renewable energy is the main lever for decarbonizing the energy system. Last year, COP28 set the goal to *'ensure three times more renewable energy capacity by 2030 [from 2022]*, or at least 11,000 GW'. While the growth of renewable energy, particularly solar, is impressive, we are not on track for the COP28 target; our model forecasts a 2030 renewable energy capacity of only 8,300 GW, or 2.2 times the 3,700 GW we had in 2022.

Comparing renewable capacity directly, however, can be quite misleading since variable solar and wind typically have much lower capacity factors than dispatchable sources like hydro or nuclear. Hence, actual electricity generated – covered extensively in Chapter 2 (Figure 2.3) – would be a better metric for comparison.

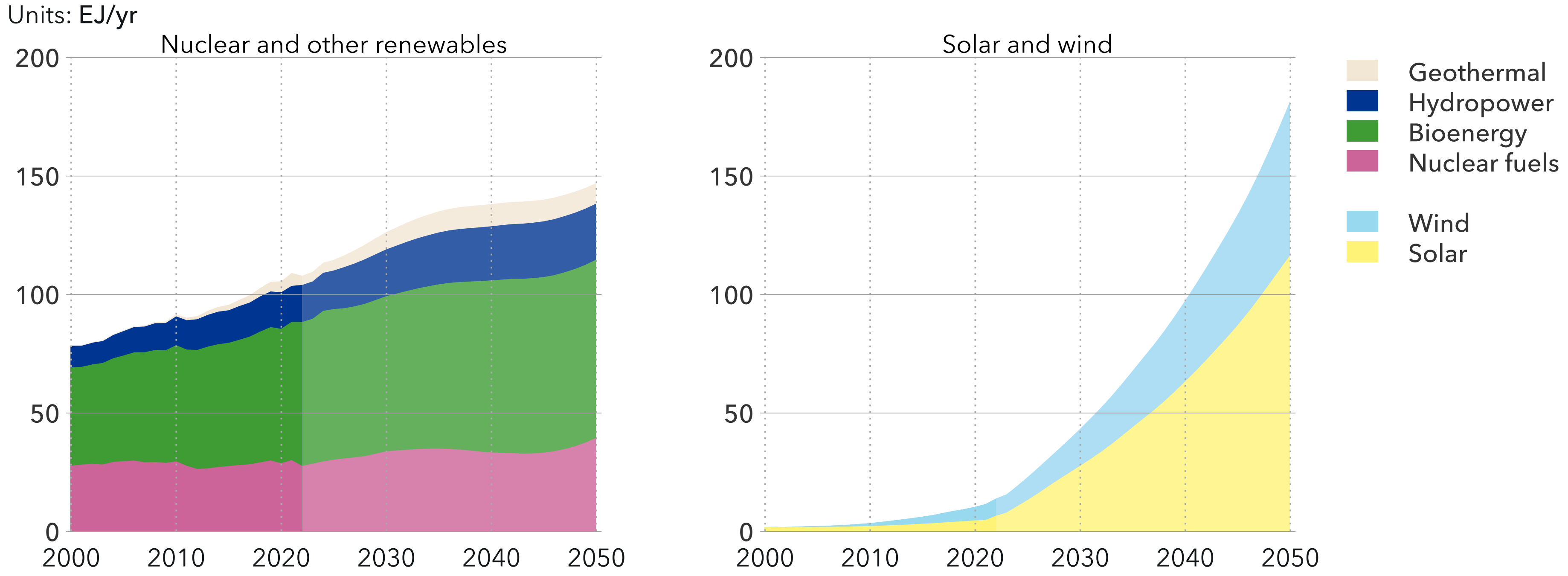
Not all renewable energy is used for electricity generation, with bioenergy being the obvious example. Much of the bioenergy in use at present is in the form of traditional biomass for cooking, a process with extremely low efficiency of typically 5% to 10%. Going forward, we will see such use of bioenergy reduce and the share of renewables dedicated to efficient electricity generation grow dramatically. The Sankey diagram at the end of Chapter 4 (Page 116) gives a full overview of the scales of production and consumption of all the different forms of renewable energy, including nuclear.

The bottom line is that renewable energy will replace fossil fuel and triple its share of primary energy supply from 15% to 44% through to 2050, while the nuclear share will grow from 5% to 6%. As most of the renewables will be used for very efficient electricity, renewables will provide well over half of the world's energy services by mid-century.

> Renewables will provide well over half of the world's energy services by mid-century.

FIGURE 3.1

World renewables and nuclear primary energy supply



Historical data source: IEA WEB (2024)

3.1 SOLAR

Solar PV has experienced remarkable growth over the past two decades. While annual solar installations comprised a modest 1 GW in 2004, by 2019 this figure had surged to 100 GW. Even amidst disruptions in 2021 caused by the COVID-19 pandemic and geopolitical tensions in North East Eurasia, solar PV added 150 GW. In 2023, installations reached nearly 400 GW. The future looks promising, with our projections indicating global installations will rise to about 540 GW annually by 2040 (Figure 3.2).

Within a decade, 20% of new PV installations will include dedicated storage, and this will increase to 57% by 2050. By mid-century, therefore, we expect solar PV capacity to reach 11 TW with an additional 5.4 TW of solar co-located with storage, bringing total PV capacity to 16.4 TW in 2050, a tenfold increase from 2023.

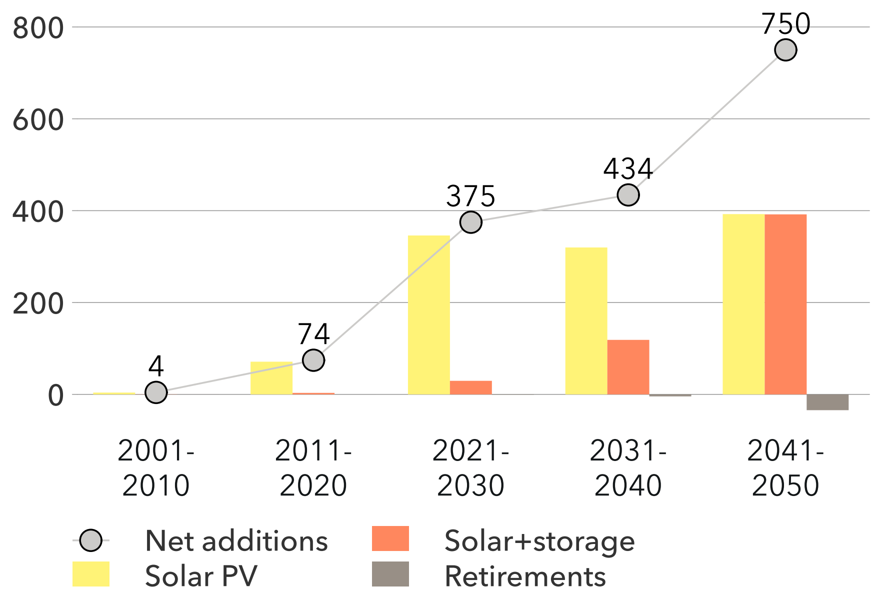
By 2050, solar will comprise 56% of installed grid connected generation capacity but only 44% of global on-grid electricity generation. This disparity is due to the lower efficiency or capacity factors of solar power compared with other renewable sources like wind and hydropower. Nevertheless, decreasing costs are driving the rapid and continuing expansion of solar. It has already established itself as the most cost-effective form of electricity in many regions, although the pace of further cost reductions in PV will slow down over time.

As solar PV becomes more prevalent in the energy mix, its economic dynamics will shift. Initially, solar PV primarily reduces the need for conventional energy during daylight hours. However, with higher market penetration, solar (along with wind) can often meet or exceed power demand and drive electricity prices to near-zero or even negative values. This shift highlights the importance of storage systems, particularly co-located solar+storage systems.

FIGURE 3.2

Global solar capacity additions and retirements, 10-year average

Units: GW/yr



Historical data source: GlobalData (2024), IRENA (2024)

Cost leadership

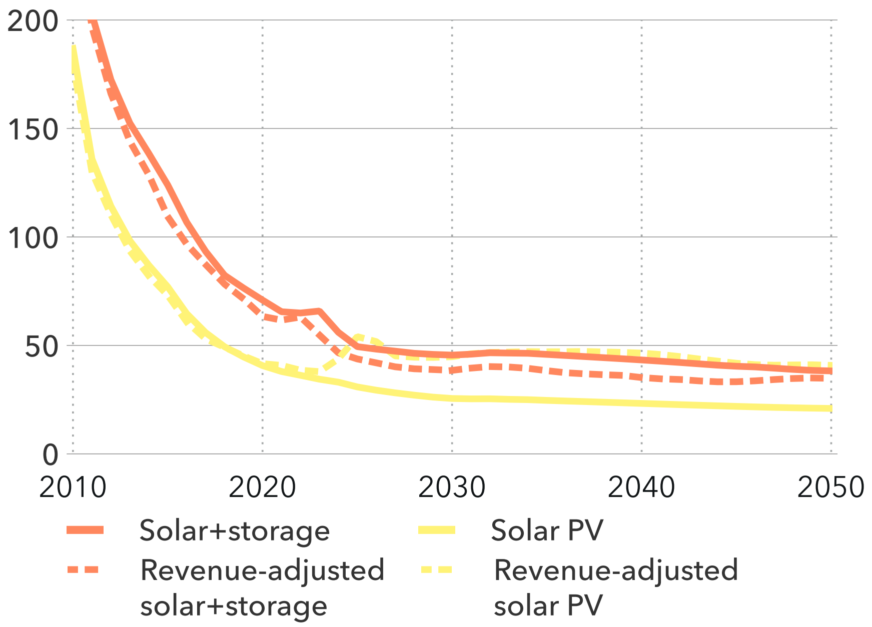
Solar's cost competitiveness is driven by its declining levelized cost of energy (LCOE). Currently, the global average LCOE for solar PV is around USD 34/MWh and USD 66/MWh for solar+storage. Looking ahead, we expect the LCOE for solar PV to drop to about USD 21/MWh by 2050 (Figure 3.3), with some projects costing even less than USD 20/MWh. This decline is fuelled by reduced unit investment costs, which now average USD 740/kW. As solar PV installations continue to increase, these costs are projected to fall below USD 650/kW by 2030 and further decrease to USD 550/kW by 2050.

A central aspect of the plunging costs of solar is its learning rate, which reflects the decrease in costs with every doubling of solar production capacity. The current learning rate for solar module costs is 26%, but this will slow to around 17% by 2050. This deceleration in cost reductions occurs as cost components eventually adjust to decreasing expenses. Despite the slower rate of cost reduction, solar PV is set to remain the cheapest new electricity source globally, except in areas with less favourable irradiation conditions like the higher northern latitudes. We expect the learning rate for operational expenses (OPEX) to remain steady at 9% until 2050 thanks to advancements in data monitoring and efficient maintenance practices.

FIGURE 3.3

World average levelized cost of solar energy

Units: USD/MWh



Historical data source: GlobalData (2024), IRENA (2024), DNV analysis

Enhancing revenues through storage

Our ETO model follows levelized profitability accounting for both price and costs, with both summarized by revenue-adjusted LCOE (Figure 3.3). This approach better reflects the competitiveness of generation technologies as investment choices given that some, such as solar PV, are fundamentally variable.

Although solar+storage systems incur a cost premium, they also offer a unique revenue advantage. These systems can store excess energy during peak sunlight hours and sell it when prices are higher, giving them an edge over standalone solar PV. The figures on page 59 show how solar+storage allows solar energy to be used at night and how it can take advantage of higher prices during an example week in 2050 for Europe.

This revenue advantage is already evident in the revenue-adjusted LCOE by the late 2020s, where solar+storage will outperform regular solar PV in terms of revenue (Figure 3.3). By 2040, we expect that most global solar capacity additions will include storage. The combination of solar and storage not only boosts revenue, but also results in cost savings. Shared costs related to permits, site selection, equipment, and grid connections reduce initial investments. In addition, on the operational side, combined systems benefit from reduced transactional expenses.

The tandem use of solar and storage offers significant cost advantages. For instance, in the US before the 2022 *Inflation Reduction Act* (IRA), co-located storage projects enjoyed nearly 30% capital cost benefits from government incentives. The IRA changed the cost landscape by explicitly supporting standalone storage, but the previous financial support for co-located storage propelled North America to the forefront of solar+storage developments.

However, co-location still has its challenges. Sites ideal for solar might not be optimal for storage. Standalone batteries, which buy power low and sell it high, might outcompete the batteries collocated with storage. Nonetheless, with declining battery prices and solar modules, both co-located and standalone systems will play a crucial role in the future energy landscape.

Regional trends

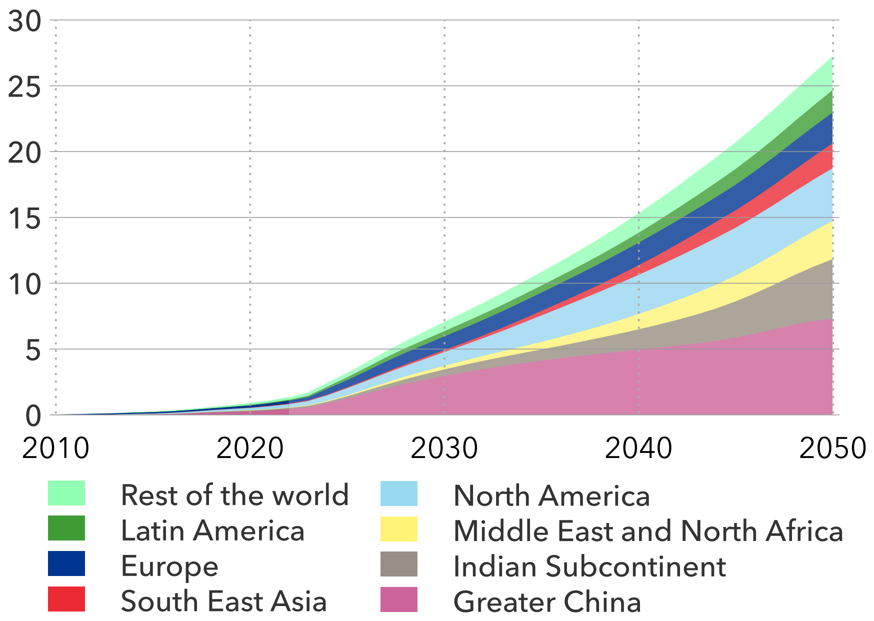
By 2050, we anticipate that Greater China, the Indian Subcontinent, and North America will lead in solar energy. However, it is important to analyse region-specific developments to understand the broader picture.

Greater China secured its position as the front-runner in 2023 by producing 32% of global solar electricity, while North America trailed behind at 18% (Figure 3.4). While Greater China and North America will remain dominant in the solar energy hierarchy, other regions will substantially boost their presence in global solar generation. In particular, the Indian Subcontinent will nearly triple its share from 6% in 2023 to almost 17% in 2050, securing second place in global generation after Greater China and even slightly surpassing North America. Meanwhile, the Middle East and North Africa quadruples its solar share from 3% each in 2023 to 11% by 2050, making it the fourth region in terms of global generation ahead of Europe and OECD Pacific. Only one region, North East Eurasia, will continue to lag, contributing a mere 0.8% to the global solar electricity share.

FIGURE 3.4

Grid-connected solar PV and solar+storage electricity generation by region

Units: PWh/yr



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

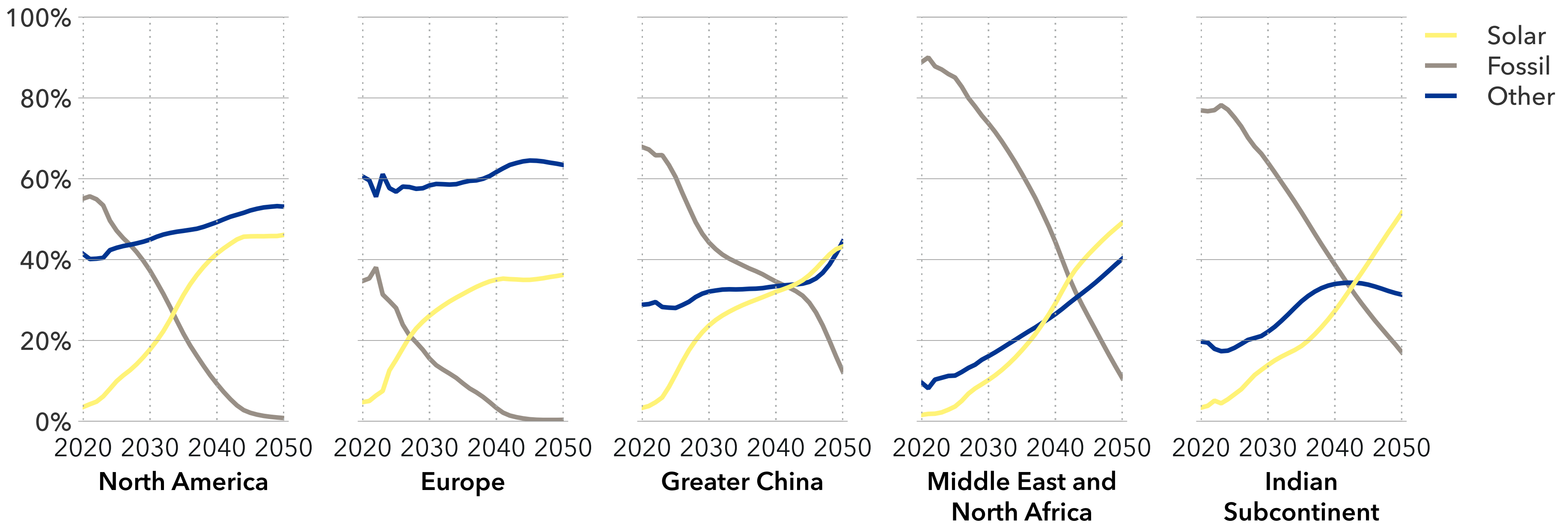
We see a universal increase in solar's share in total generation from 2020 to 2050 across all regions. The overwhelming surge in solar will come predominantly at the expense of declining fossil generation rather other renewable energy sources, but the pace and reasons for this shift differ.

Europe, with its world-leading decarbonization agenda and supportive solar policies, will witness solar surpass fossil-fuel generation before 2030 (Figure 3.5). The Middle East and North Africa region, abundant with high solar irradiation, will harness solar for almost half of its electricity by 2050. The region’s inclination towards solar is further enhanced by the relatively limited presence of other variable renewable energy sources (VRES) like wind. Nevertheless, in the case of the Middle East and North Africa region, prolific and often generously subsidized domestic oil and gas resources delay the point at which solar surpasses fossil in electricity generation until almost 2040. North America's solar expansion, on the other hand, owes its trajectory to compelling economics and strengthened policy endorsement.

FIGURE 3.5

Share of solar, fossil fuel, and others in grid-connected generation in selected regions

Units: Percentages



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

Lastly, the Indian Subcontinent is set to surpass a 50% share of solar in electricity generation in that region by 2050 – a higher share than both Greater China and North America. This will necessitate a connection of about 2.6 TW of solar capacity to the grid, second only to Greater China's almost 5 TW, with the latter representing 16% of the total solar capacity set to be installed by 2050 (Figure 3.6).

Off-grid solar capacity

Beyond the grid, we see the rise of off-grid solar, particularly for hydrogen production and to serve isolated, often rural, demands. By 2050, about 700 GW of off-grid solar, or 2.2% of total solar installations, will be dedicated to hydrogen production, predominantly in Greater China (51%), OECD Pacific (26%), Europe (12%), and North America (5%) (Figure 3.7). This substantial allocation underscores the critical role of solar energy in supporting the hydrogen economy, enabling regions to produce clean hydrogen independently, reducing reliance on fossil fuels and advancing their energy security.

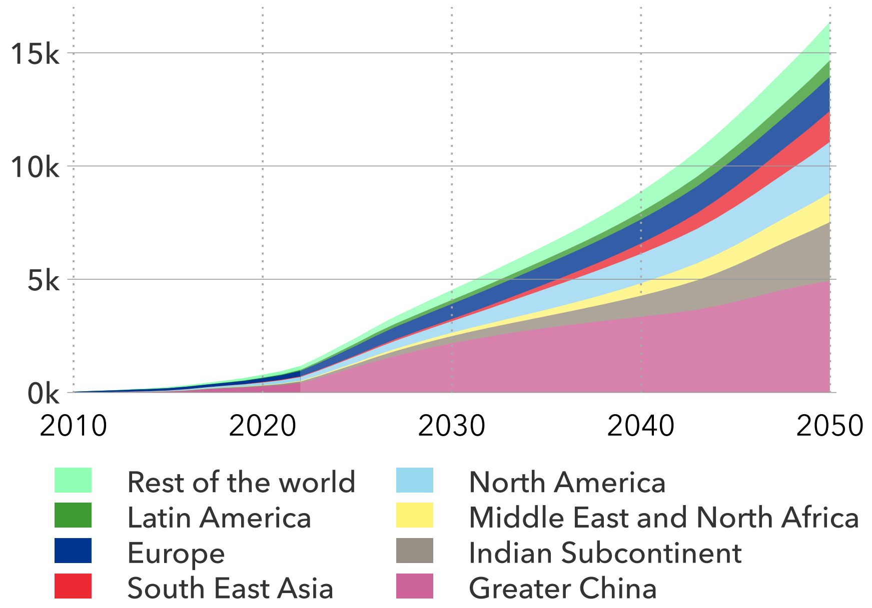
In addition to its role in hydrogen production, off-grid solar is poised to make a significant impact in remote regions. Approximately 113 GW of off-grid solar capacity will be deployed in remote areas in Sub-Saharan Africa (70%) and the Indian Subcontinent (30%). These installations will bring life-changing electricity access to communities that have historically been underserved, transforming daily life by powering homes, schools, and healthcare facilities, and fostering economic development. These regions, despite their geographical challenges, offer vast untapped solar potential and hold the promise of transformational energy independence. Solar installations in these areas can bypass the need for extensive and costly grid infrastructure to provide a more immediate and sustainable solution to energy access.

This narrative underlines the future duality of vast centralized powerhouses on the one hand, while on the other, we witness the rise of decentralized, individualized energy systems. The dual approach not only diversifies the energy landscape but also enhances resilience, allowing different regions to leverage their unique solar potential effectively.

FIGURE 3.6

World grid-connected solar capacity by region

Units: GW



Historical data: GlobalData (2024), IRENA (2024)

Sensitivities

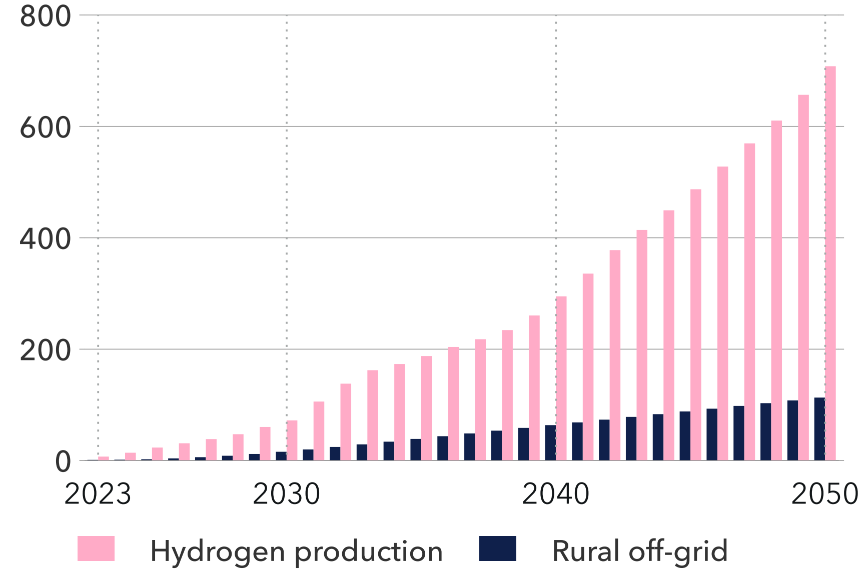
Solar PV's deployment remains consistent across different carbon price assumptions. In our extensive model testing, we found that the impact of carbon prices on solar PV is minimal. Thus, its positioning and growth is not heavily reliant on fluctuating carbon prices.

> In our extensive model testing, we found that the impact of carbon prices on solar PV is minimal.

FIGURE 3.7

Globally installed solar off-grid capacity

Units: GW



Solar PV expansion land use

We forecast a twelve-fold increase in solar PV capacity (including off-grid) by 2050. Sufficient land and buildings with suitable rooftops are prerequisites for such expansion. Solar PV installations will include utility-scale projects, microgrids, rooftop installations, and off-grid setups for hydrogen production. Solar PV expansion for non-rooftop solar-PV installations indicates a land-area requirement of less than 1% of total land area globally in 2050.

Even for regions with large shares of solar PV in their power mix, the land-area requirement is not unmanageable. For example, 3% of agricultural land in Greater China and South East Asia will be used for solar PV installations in 2050. Co-use of land for grazing or for certain types of agriculture is also possible. It therefore seems unlikely that the expansion of solar PV will encounter land-area limitations overall.

For more details and an in-depth analysis, see Appendix 4. Readers may also be interested in NREL's leading and ongoing research into agrivoltaics – the pairing of solar with agriculture.

Tilling the soil at the largest agrivoltaic research project in the US – Jack's Solar Garden, in Longmont, Colorado. (Photo by Werner Slocum / NREL)

Biodiversity

Biodiversity is a wide term that refers to the variety of life on earth including genetic differences within species. Biodiversity considerations in our work include both the human aspects of valuing nature, and the intrinsic value of nature itself.

This year, DNV researched social aspects of the energy transition and related pushback (see fact box on Page 134). There is an interface between biodiversity and social aspects of nature, such as recreational activities or visibility of human settlements. We aim to keep these issues separate to avoid overlap and double counting in our quantification.

It has become apparent in the last few years, that biodiversity concerns are going to play an increasingly important role in the energy transition. The adoption of the *Kunming-Montreal Global Biodiversity Framework* (GBF) in 2022 has further strengthened biodiversity priorities; today's authorities, industries, finance, and communities put biodiversity considerations into their decision making. This is a trend we expect to strengthen and widen into more sectors and geographies. Regulations, particularly in Europe, are tightening to protect biodiversity, including the globally leading UK regulation on *Biodiversity Net Gain* which requires onshore commercial developments to result in more or better-quality natural habitats than before the development. Nationally significant infrastructure projects will need to comply with the regulations from November 2025.

Impact on Nature

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPEBES) has identified five key drivers of biodiversity loss: 1) Changes in land and sea use, 2) Direct exploitation of organisms, 3) Climate change, 4) Pollution, and 5) Invasive alien species.

One of the four goals of GBF towards 2050 is to maintain, enhance or restore the integrity, connectivity, and resilience of all ecosystems. This goal is supported by several short-term targets towards 2030. These include: protecting and managing 30% of all land, freshwater, and sea areas; restoring 30% of degraded ecosystems; ensuring management action to halt human induced extinction of species; and reducing the negative impact of pollution from all sources to a level not harmful to biodiversity. All forms of energy influence biodiversity and nature (see examples in Table 3.1). The significant requirements for acreage for development of renewable energy presently gets high attention in the context of the energy transition. On the other hand, wind farms and solar parks can have positive impacts on biodiversity by helping to preserve habitats, and a great deal of research is being conducted in how this can best be achieved (EEB, 2022).

Other activities like fossil-fuel extraction, biofuel production, mineral mining, and the construction of new transmission lines also contribute to the five drivers of biodiversity loss and require biodiversity impact assessments.

Land use changes (like clearing forests to create farmland) are currently the leading cause of biodiversity loss. However, research has now shown that climate change is likely to take over as the leading cause of biodiversity loss by 2050 (Pereira et al., 2024). Therefore, mitigating temperature increase by replacing fossil energy with renewable energy is extremely important for preserving biodiversity over time. While that should not exempt renewables from taking site specific biodiversity impacts seriously, policymakers may take into account the overall net benefit to global biodiversity when evaluating new renewables projects. Loss of nature itself, notably loss of rainforests, also accelerates global warming, resulting in a spiralling reinforcing mechanism.

How we are considering biodiversity in our analysis

We focus on how biodiversity will most likely influence the ongoing energy transition, not how it ideally *should* influence the transition based on factors like intrinsic value of nature or cost of externalities.

We expect accountability for project developers' impact on nature to become increasingly stringent and consider biodiversity implications over all life-cycle phases of projects. Accordingly, we envision that biodiversity will influence the energy transition in the following ways:

- Buildouts will likely become more expensive. Longer permitting processes will strain finances, projects will receive less support or face higher taxes, governments will enforce measures to protect nature (e.g. avoiding open-pit mines), and developers will need to pay for nature restoration elsewhere or compensate impacted humans. End of life considerations, including decommissioning and waste disposal and site restoration, also add to the costs.
- Buildouts will take more time or be cancelled. This could lead to alternative, more expensive, buildouts happening instead.
- Revenue will likely decrease. Plants may need to be built in a less optimal size or at locations that generate less energy, and an asset may be closed down for parts of the year or run at a lower output for biodiversity reasons.

The extent of these factors is uncertain and quantification is challenging, although our work taps into DNV's extensive experience in providing biodiversity-related services to the power and renewables industries. To the best of our ability, DNV includes the quantitative effects of the above factors on all sectors and geographies in our assessment of costs, capacity factors, subsidies, taxes, delays, and revenues. We will continue to research and model this in the coming years, further refining our work as our understanding of the impacts and regulatory interventions improves.

> Research has shown that climate change is likely to take over as the leading cause of biodiversity loss by 2050.

TABLE 3.1

Materiality ratings for impact drivers typically relevant for electric utilities and power generators sector (TNFD, 2024)

Driver of nature change	Impact driver	Power transmission and distribution	Fossil fuels thermal power stations	Nuclear thermal power stations	Hydropower	Wind	Biomass	Geothermal	Solar
Land / freshwater / ocean-use change	Area of land use	Medium	Medium	Medium	Medium	High	High	Low	Low
	Area of freshwater	Low	Medium	Medium	High	N/A	ND	ND	N/A
	Area of seabed use	Low	ND	N/A	N/A	Medium	N/A	N/A	N/A
Climate change	GHG emissions	Very low	Very high	Very low	Low	N/A	High	Medium	ND
Resource exploration	Volume of water use	Very low	Medium	Medium	Low	Low	Medium	Medium	Low
	Other biotic resource extraction (e.g. timber	N/A	N/A	N/A	N/A	N/A	Medium	N/A	N/A
Pollution / pollution removal	Emissions of non-GHG air pollution	Very low	Very high	Low	N/A	N/A	High	High	N/A
	Emissions of nutrient soil and water pollutants	N/A	N/A	N/A	N/A	N/A	Medium	N/A	N/A
	Emissions of toxic soil and water pollutants	Low	Very high	Medium	ND	Very low	Medium	Medium	Low
	Generation and release of solid waste	Low	High	High	Low	Very low	High	Very low	Very low
	Disturbances (e.g. noise, light)	Low	Very high	Medium	High	Medium	High	Medium	Very low

N/A – Not applicable. ND – No data.
Source: ENCORE Partners (Global Canopy, UNEPFI, and UNEP-WCMC) (Unpublished, Expected 2024). ENCORE: Exploring Natural Capital Opportunities, Risks and Exposure. Cambridge, UK: the ENCORE Partners. Available at: encorenature.org and DOI: doi.org/10.34892/dz3x-y059.


Photo by Werner Slocum / NREL

3.2 WIND

From providing 7% of grid-connected electricity generated in 2023, we forecast global wind electricity will contribute 28% of global electricity generation by mid-century, corresponding to an 8% year-on-year growth in generation. By 2050, total global wind power capacity will be 6.3 TW, from 1.0 TW in 2023, and constitute a little less than one-fourth of total grid-connected capacity. Offshore wind has faced post-pandemic headwinds, principally supply chain snarl-ups and cost inflation, but is now recovering some lost ground as interest rates start to fall, governments sweeten auctions, and several new markets open up. However, the stalled momentum reverberates through our long-term forecast, with offshore wind installed capacity in 2050 at 20% lower than last year's forecast.

Figure 3.8 presents the share of wind energy in electricity generation by region for the years 2023 and 2050. For 2050, we differentiate between three types of wind turbines: onshore, fixed offshore located in shallower waters near the shore with bottom-fixed foundations, and floating offshore situated in deeper waters (over 50 metres) with floating foundations.

Globally, the three types of wind electricity combined to account for 7% of the generation in 2023. Onshore wind provided four times more power than offshore wind. There are also stark regional differences: wind contributed minuscule amounts in fossil fuel abundant regions such as North East Eurasia and the Middle East and North Africa, while it contributed over 15% in Europe.

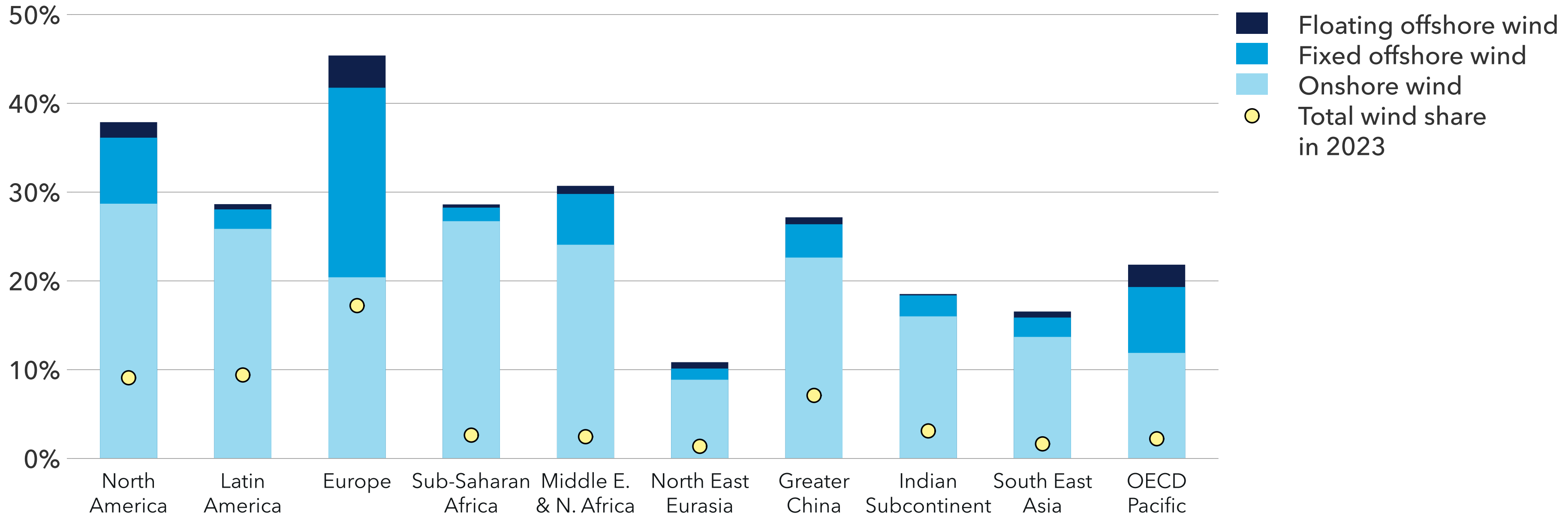
By 2050, all regions will see growth in wind electricity generation in their power grid. Europe and North America will have as much as 46% and 38% wind in their electricity mix, respectively, but North East Eurasia is likely to continue to rely on its domestic fossil-fuel resources and will have only about 10% of wind in its electricity mix.

Over the next decade or so, demand for wind energy (together with solar) will largely be driven by new demand growth for electricity. After that, wind power and solar will increasingly replace fossil-fired capacity at a global level. That is of course already happening at a regional level, for example in Europe, where wind power has already replaced coal in several countries and is starting to displace natural gas in the power mix. Europe and North America are accelerating the retirement of ageing fossil-fuel power plants and the deployment of new wind farms. Moreover, national decarbonization and renewable energy targets around the world make wind power

FIGURE 3.8

Share of wind in electricity generation in 2050 by region

Units: Percentages



Historical data source: IEA WEB (2024) GlobalData (2024) essential for meeting this new demand alongside solar energy. The expansion of wind power is further supported by substantial cost reductions achieved over the past two decades, despite recent cost escalations. Additionally, the rising carbon prices adopted by many regions are making wind power an increasingly economical choice.

From a generation perspective, wind energy often complements solar energy, particularly during the winter months when solar generation declines (also during nighttime when there is no sun, but stronger winds in some places). While wind power is an intermittent resource, its variability is less pronounced on a daily basis and it complements demand better, making it a more reliable electricity source in many locations.

Finally, manufacturing wind turbine and associated power components is increasingly recognized as a strategic priority in several key regions, including Greater China (DNV, 2024), North America (DNV, 2023a), and Europe (Europe Regional Chapter). In the global competition to lead in clean technology, strong economic and strategic incentives are driving these regions to either bolster their domestic wind power industries or strengthen their positions as market leaders and promote wind energy in their electricity mix to stimulate demand.

Onshore versus Offshore wind

In 2023, global onshore wind electricity generation far exceeded offshore wind (both bottom-fixed and floating) by a ratio of nine to one. Onshore wind farms are generally easier to construct and maintain due to better access to transmission lines and proximity to population centres. In contrast, offshore wind farms face higher construction costs due to the specialized materials required, foundations needed, logistical challenges in transporting equipment to sea, and delays related to siting and permitting offshore cables and substations.

However, we anticipate a significant narrowing of this gap by 2050. The current nine-to-one ratio will shrink to three-to-one. Several factors contribute to the projected growth in offshore wind alongside the continued rise of onshore wind. Technological advancements in offshore wind farm construction are rapidly reducing costs, making these projects more economically viable each year. Additionally, countries with experience in offshore oil and gas operations are leveraging their expertise to develop and manage offshore wind farms.

The availability of suitable land for economically profitable onshore wind farms is limited in many regions. Some areas are running out of prime windy sites, and there are increasing objections to onshore wind farms due to concerns about visual and noise pollution, as well as high land costs near commercial centres. For coastal cities, such as those on the eastern seaboard of the US and Canada, offshore wind farms can be closer to urban areas than onshore alternatives.

Moreover, wind speeds are generally higher at sea so, on a levelized cost basis, offshore wind projects can sometimes be more cost-effective than certain onshore wind projects.

Installed capacity

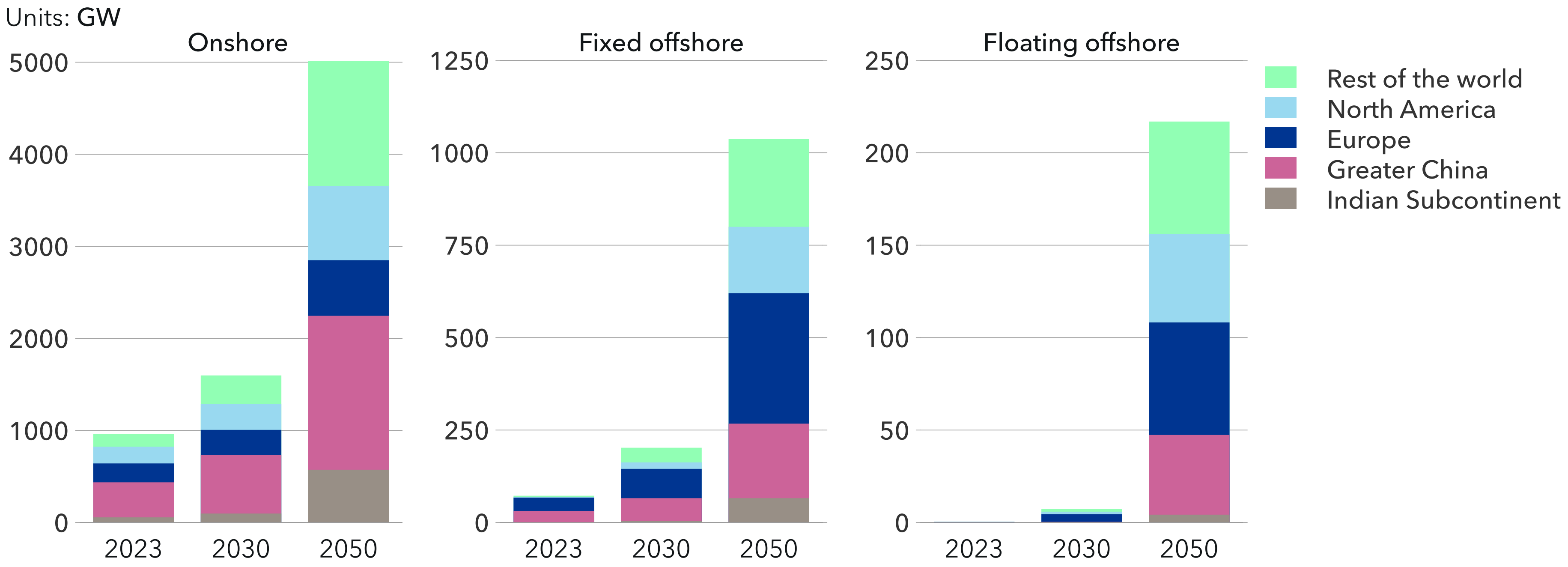
Wind energy generation in a region or country is a function of the installed power capacity of turbines and how windy the region is. Actual generation is also impacted by maintenance regimes, turbine efficiency or performance and grid capacity to export power.

Total installed capacity of wind power in 2023 was 1 TW, 93% of which was onshore wind turbines. We expect total wind capacity to grow to 1.8 TW by 2030 and reach 6.3 TW GW by mid-century.

Some interesting trends emerge when we break down these numbers by region (Figure 3.9). Greater China stands out as the dominant player in both onshore and fixed offshore capacities. This surge is not just due to the rapid rate of installations but is also fuelled by economic incentives from the region's emerging carbon market in the power sector. Furthermore, for decades, the region has encouraged the wind turbine industry to flourish, so it is primed to compete with well-established wind market players in other regions. To that end, Greater China has the luxuries of production overcapacity and state support. This places them in a good position to compete on cost and price for projects being developed in many other regions, although China will encounter stiffening tariff barriers in some key markets (DNV, 2024).

FIGURE 3.9

World installed wind capacity by region

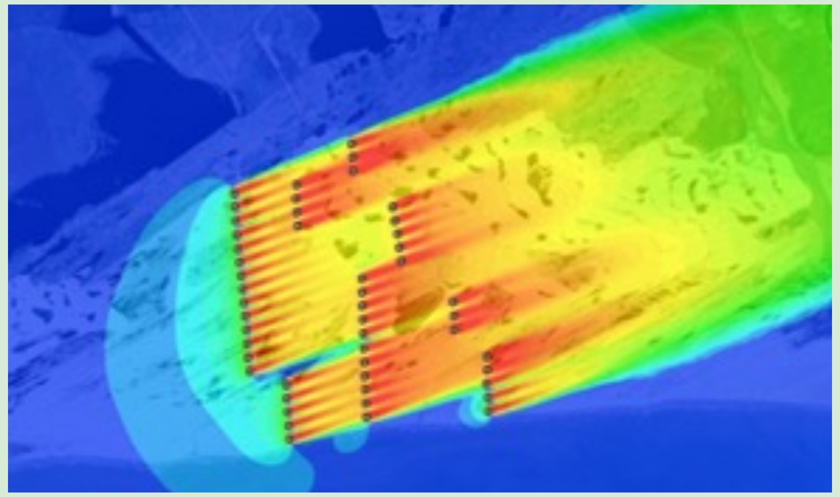


Historical data source: GlobalData (2024), DNV analysis

Combating wake losses

Offshore wind farms can have significant effects on each other via turbine interaction effects (also referred to as wake and blockage effects). These effects extend over long distances over the ocean due to the lack of topology and surface roughness of the sea. This means that production for clustered projects will be lower than projects built in isolation. This must be factored into the production estimates for offshore wind projects where the proximity of neighbouring wind farms is an issue. Significant progress has been made in modelling these complex interactions in recent years.

Engineering wake models have been available in wind farm design software, such as WindFarmer, for 25 years to help wind farm developers understand the critical reductions in available energy through wake and blockage losses, and design better wind farms. Rapid engineering wake modelling approaches have been validated and tuned against the biggest wind farms operating today, but not against the planned mega-clusters of tomorrow. To reduce wake modelling uncertainty that is increasing with wind farm scale, DNV developed high-fidelity CFD wake modelling capability, but this is computationally intensive. An alternative approach is underway to train a machine learning surrogate model, CFD.ML, on the high-fidelity model results to provide enhanced and expedited turbine interaction modelling, simplifying full CFD models.



On the other hand, Europe is shaping up to be the leader in the floating offshore wind market, particularly by leveraging developments in the North Sea. Despite limited land availability, Europe possesses the technical capacity to build and maintain offshore wind sites in deeper waters, allowing it to look to its seas for wind power. Furthermore, these offshore sites have stronger wind resources than sites on land, and from a revenue perspective, wind speeds are often higher in winter months when electricity demand peaks.

Beyond these figures, it is worth noting that wind power will serve more than just our electricity needs. A dedicated portion of this capacity will be specifically geared towards hydrogen production through electrolysis. Our forecasts indicate that by 2050, there will be 265 GW of onshore and 35 GW of fixed offshore wind capacity dedicated solely to hydrogen production.

For two years in a row, we have revised our forecast downwards for wind power generation and capacity, compared to the previous year forecast, especially for 2030. This revision has been a result of observing wind power projects, especially in the fixed and floating offshore wind markets. In last year's *Energy Transition Outlook* (DNV, 2023b), we detailed the roadblocks.

In short, high interest rates and higher cost of capital, dwindling profits and margins for OEMs, supply chain delays, rotor and turbine quality issues, and local content requirements in many nascent and growth markets all combined to increase the cost of wind projects in regions such as North America (Richard, 2023) and Europe. At the same time, costs in some specific regions are deflated thanks to production overcapacity and government support, which also has the effect of preventing established players in other regions competing on cost (Radowitz, 2024). Now, as we enter the final quarter of 2024, there are indications of some recovery due to falling interest rates, governments sweetening auctions for offshore wind, and the opening up of several new markets.

Levelized cost of wind electricity

The LCOE of wind plays a critical role in the quantity of wind capacity coming online in different regions. There are two important factors that affect LCOE: annualized CAPEX + OPEX costs of wind; and the total electricity generated over the lifetime of the wind power plant, a function of the windiness of the site and the turbine size.

The global average LCOE of onshore, fixed offshore, and floating offshore wind will continue to fall through to 2050 (Figure 3.10). In the period leading up to 2021, several factors caused the LCOE to fall:

- Developments in turbine technology allowing the optimal use of lower wind speed sites in developed markets
- Improved operational efficiency of the wind power plants in developing markets
- Technical developments led to lower capital costs
- Manufacturing volumes and standardization lowered capital costs
- Smarter operations lowered operating costs and improved operational efficiency
- Lower material and labour costs

> From a generation perspective, wind energy often complements solar energy.

From 2021 to 2024, wind LCOE increased in most regions due to heightened material and labour costs, delays in material delivery, and higher cost of capital. (Figure 3.10).

From a 2023 baseline of USD 49/MWh for projects, we anticipate the global weighted average LCOE for onshore wind will drop marginally to USD 43/MWh by 2030. The impact of the current wind power woes will continue to be felt until the 2030s and slow the reduction in LCOE. From 2040, the reduction in LCOE will pick-up speed again and reach about USD 28/MWh by 2050. Faster development in nascent markets, such as Sub-Saharan Africa and the Indian Subcontinent, contributes to this reduction in the 2040s.

The near-term future of fixed and floating offshore wind LCOE is a bit bleaker than for onshore wind. The recent increase in offshore wind LCOE has delayed and cancelled projects, even in developed markets such as North America (EIA, 2024) and Greater China (Huang, 2024). In 2023, the global average fixed offshore wind LCOE was USD 133/MWh, up 30% from 2020. While these elevated LCOEs are temporary, we expect it will be 2030 before the LCOE returns to USD 100/MWh. Over the long term, the access to the windier sites and heightened operational efficiencies that are possible in offshore wind make us optimistic and we expect fixed offshore wind LCOE to reduce to USD 67/MWh by 2050. However, this will still average about two and a half times more than the LCOE for onshore wind.

Currently, the LCOE for floating offshore wind (USD 290/MWh) is more than twice that of fixed offshore wind (USD 133/MWh). By 2050, we expect the global average LCOE for fixed offshore wind to be around USD 67/MWh and floating offshore at approximately USD 96/MWh, a difference of only 45%. These cost reductions will be driven by volume increases and the advantages of experiential learning.

While the global average LCOEs give some interesting insights, they mask regional differences in the development of LCOEs, especially in the critical fixed offshore wind category (Figure 3.11).

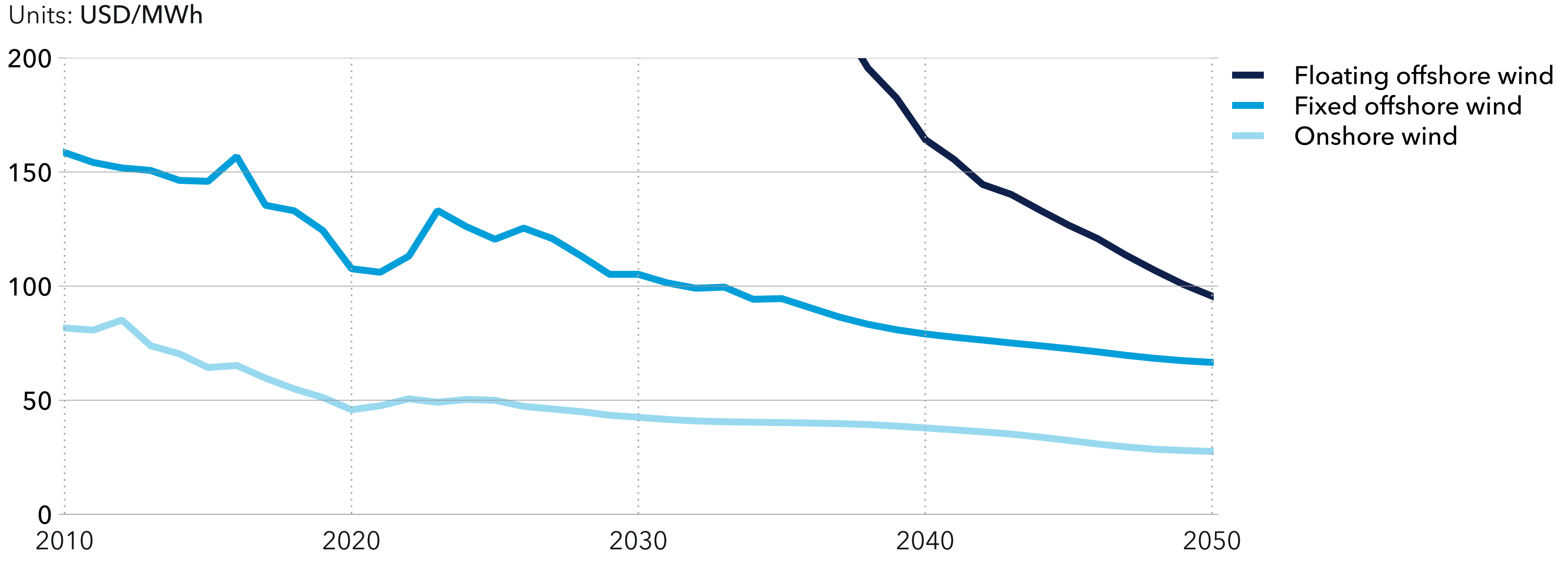
Not all regions have the same cost trajectories. Greater China experienced only a marginal increase in LCOE from 2021 to 2023, while Europe, North America, and South East Asia have all seen more significant increases of 15% to 25%. China's advantage is linked to its production overcapacity and the support its domestic wind industry receives from beneficial policies. We do not expect LCOE in Greater China to reduce much further from late 2030s to 2050.

Until 2030, the gap in LCOEs between Greater China and the other regions is large. However, we see their LCOE reducing dramatically in other regions once the issues with higher cost of capital and material and labour costs start easing. In the case of Europe, we even expect the LCOE to reach parity with Greater China's LCOE by the 2030s, and even undercut it by the mid-century.

Of the four regions featured in Figure 3.11, South East Asia has the highest LCOE from 2020, twice the LCOE of Greater China. This is because the offshore wind industry is in its infancy there. However, we expect South East Asia and similar regions to have developed their offshore wind infrastructure by 2050. At this point, the learning-by-doing effect will start to be reflected in the sharp drop in LCOE, which will only be about 50% more than that of Greater China.

FIGURE 3.10

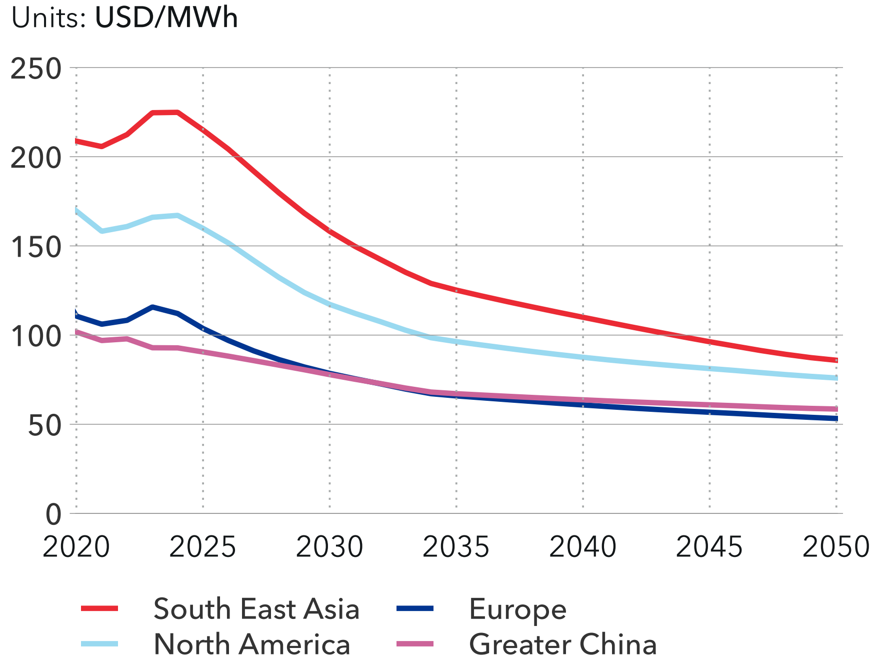
World average levelized cost of wind energy



Historical data source: GlobalData (2024), DNV analysis

FIGURE 3.11

Regional levelized cost of offshore wind electricity



Biofouling community on an offshore fixed-bottom wind turbine, including blue mussels, plumose anemones, sea urchins, common starfish, barnacles, and tubeworms (Degraer et al., 2020). Photo credit: Royal Belgian Institute of Natural Science; Alain Norro

Wind: spatial impact

We forecast a six-fold increase in wind power capacity (including off-grid) by 2050. It is reasonable to question whether there is enough land to accommodate this expansion, but it is not land per se that is the limiting factor. Onshore wind has a relatively small footprint, effectively just the base of the tower. The overall land area demand, including space between each turbine, equates to less than 1% of available land. In comparison, this is only about 2.2% of the land used for agriculture. At the most extreme, South East Asia will need to use 10% of its available land, only 3% of its agricultural land.

Rather than land, it will be peoples' collective acceptance of visual, noise, and other environmental and societal impacts associated with land-based wind power. Siting tall, rotating structures in densely populated areas or in pristine and vulnerable biodiverse locations is a growing societal concern. People are pushing back against wind farms in their neighbourhoods and some natural sites are now safeguarded through the *Kunming-Montreal Global Biodiversity Framework*.

Offshore wind potentially avoids both the land and societal issues by being located far from populations. Globally there will be enough sea areas and coastline to accommodate the forecast amount of offshore wind. However, when considering the maximum technical capacity, only a small fraction of the installations will be floating offshore wind. For regions with large amounts of fixed offshore wind close to land, a significant area will be used for installing wind turbines. For example, a region like Greater China will utilize almost 17% of its coastline for offshore wind. Such intensive buildouts are fuelling concerns regarding biodiversity and society that will need to be managed to successfully install such large amounts of offshore wind. In particular, science-based approaches will need to consider the sum of positive impacts (e.g. biodiversity boosts like no-trawl zones and foundations acting as artificial reefs) and negative impacts (noise and ecosystem disruptions coupled with the challenges of co-existence with other ocean industry demands). For more details see Appendix 4.

3.3 HYDROPOWER

Hydropower generation poised for growth. In fact, we forecast that it will expand by close to 50% by 2050. While important, this growth is dwarfed by the massive expansion of solar PV and wind over the same period. So much so, that the share of hydropower in global grid electricity generation reduces from 14% now to below 11% in 2050.

Forecast: Greater installed capacity and generation
Hydropower generation has doubled in 20 years (Figure 3.12). However, its total potential is limited by topographical constraints, and for each new completed project the remaining capacity potential is reduced. Hence, growth will gradually slow.

Our model indicates an increase of 43% from 1,400 TW to 2,000 TW installed hydropower capacity by 2050 with distinct variation between regions between regions (Figure 3.12). Greater China will have more than a quarter of the total installed capacity by mid-century, followed by the Indian Subcontinent, Latin America, and Europe with similar shares of around 10% to 12%.

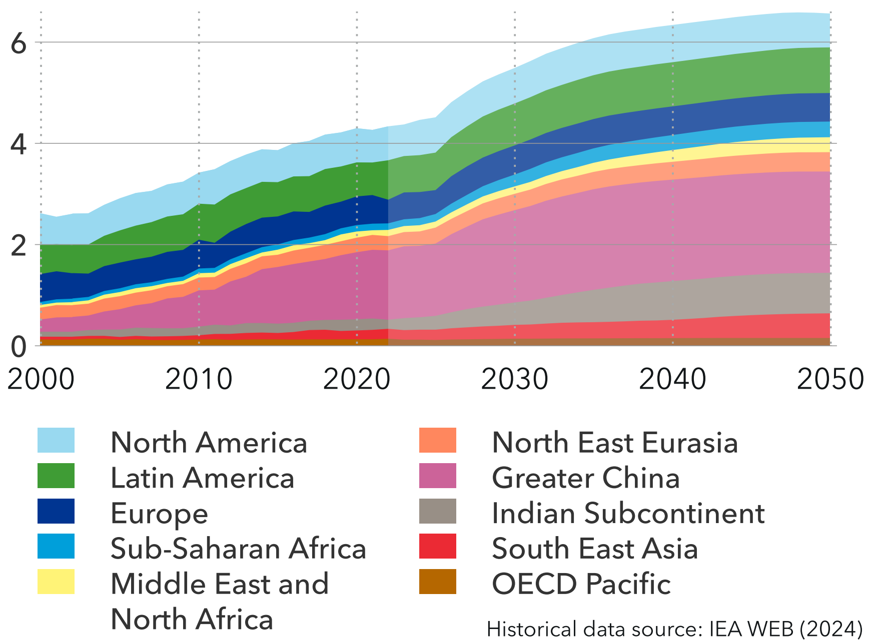
Pumped hydro as an optimizer of grid flexibility
As solar PV and wind energy expand quickly, there is increasing need for dispatchable power to provide grid flexibility for managing daily and seasonal variations. Hydropower is excellent from this perspective, being both zero-emission and easy to turn on and off as needed. Hydropower, including pumped hydro, will be second only to Li-ion batteries as a flexibility provider for the grid in 2050.

Pumped hydro provides additional benefits to traditional hydropower as it can store energy from solar and wind resources – in the short or medium term – by pumping water up in periods with surplus in the grid and releasing it to produce electricity when needed.

FIGURE 3.12

Hydropower electricity generation by region

Units: PWh/yr



Historical data source: IEA WEB (2024)

Aerial view of the upper reservoir of the Markersbach pumped storage power plant, Saxony, Germany.

Hourly electricity price variation is the main driver for increased use of pumped hydro. Variation may incentivize pumping at night during low electricity demand and delivering power through the day. Alternatively, market fundamentals may favour daytime pumping on sunny and windy days to deliver electricity profitably at night when the VRES deliver less or no power. Liberalized markets see more price variation and therefore increasing incentive for further building of pumped hydro. This also allows pumped hydro to receive higher average prices and ensure profits despite having a higher LCOE than wind and solar PV. This is also financially interesting for traditional hydropower in grids with more input from VRES and therefore more hours with greater price differences.

We foresee a global pumped hydro storage capacity tripling by 2050. However, for short-term storage, it will meet increasing competition from battery storage projects in the grid and from storage at the end-consumer (sometimes behind the meter) as batteries will have competitive costs, scalability, and installation time. We predict that pumped hydro in 2050 will account for only 15% of the total storage capacity (not including traditional hydro) compared with more than 90% today. Different battery options will provide the bulk of the storage capacity in mid-century.

Greater China and Europe have similar installed capacity today, but China's will grow 4-fold by 2040 while Europe sees almost no increase. Europe's expansion will be limited by strict regulation and thorough assessments of biodiversity and other environmental aspects in the approval process. A simpler regulatory regime, pumped hydro will grow more in North America than in Europe, but each region will have just above 10% of the total global installed capacity in 2050.

A power source affected by climate change

Global warming is challenging the prevailing view that hydropower is the most reliable source of power. Climate change accelerates melting of mountain glaciers, induces greater rainfall variations, and leads to faster snow-melting and recurrent droughts. Even if absolute precipitation is likely to increase with higher temperature (each 1°C of warming allows 7% more water content in air), the changes create increased uncertainty over future hydropower output, with varying regional impacts. A report on hydropower generation in the US concluded that generation might reduce by up to 2% over 40 years in the drier southern regions and increase up to 10% in wetter northern regions of the country (US DOE, 2023). A recent example (Ryan, 2024) for one US run of river shows much higher vulnerability as the snowpack is reduced.

Preliminary numbers on global hydropower generation in 2023 are down 1,8% from previous year and down 7% for China alone (EIU,2023). If such a reduction in capacity factors transpires, it will also influence modelling of future hydropower deliveries.

Furthermore, hydropower has a dual purpose to generate electricity and manage water resources for flood control and irrigation. Ensuring that hydropower schemes are equipped to manage the coming challenges in rainfall and weather patterns reduce damage to local communities and crops in extreme weather conditions. This requires broader assessments of risk to be integrated throughout approval processes and during operations.

> Climate change accelerates melting of mountain glaciers, induces greater rainfall variations, and leads to faster snow-melting and recurrent droughts.


Photo by Prateek Joshi / NREL

3.4 NUCLEAR POWER

Nuclear power has historically provided a reliable, carbon-free source of continuous electricity at a reasonable cost. Nuclear energy has also traditionally been thought of as a national asset that contributes to energy independence.

Following the 2011 nuclear accident at the Fukushima Daiichi plant in Japan, projects were delayed and new build slowed down, while Germany decided to phase out nuclear power plants. This posed significant challenges for the nuclear industry. Even before the Fukushima disaster, new build costs – exacerbated by project delays associated with complex third-generation plants – in developed countries had been spiralling alarmingly. Nuclear energy has struggled to compete with both traditional fossil fuels and emerging renewable energy sources. Despite this, the renewed focus on energy security, spurred by the war in Ukraine, has prompted many regions to reconsider nuclear power. This reconsideration is largely linked to the desire to establish energy independence in a geopolitically fragmenting world, because dispassionate analysis (Squassoni, 2024) of events in Ukraine and in the Middle East underlines the vulnerability of nuclear plants to widening tension and war.

Nuclear energy offers a stable electricity supply with less dependence on high-volume fuel imports, such as with natural gas, although access to uranium, and specifically enriched uranium, fuel can be an issue. The private sector nuclear industry expects significant market growth, at least in the OECD, driven by the development of Small Modular Reactors (SMRs) which aim to standardize technology, harmonize regulatory regimes, reduce costs, and improve cost predictability. The same ambitions are driving growth in developing countries, but focused to a greater degree on large scale reactors. Additionally, the recent global commitment to biodiversity could further challenge renewables use of surface space, where nuclear has a clear advantage.

However, even if SMR manages to deliver on its promise, future nuclear power will have to compete with the continuous cost decline of renewables and solve the existing challenges facing today's nuclear fleet, including:

- Long term waste management
- Construction time and budget overruns
- Concerns around the risk of nuclear proliferation
- Risk of lower utilization with high renewable penetration
- Providing flexibility without increasing cost per kWh

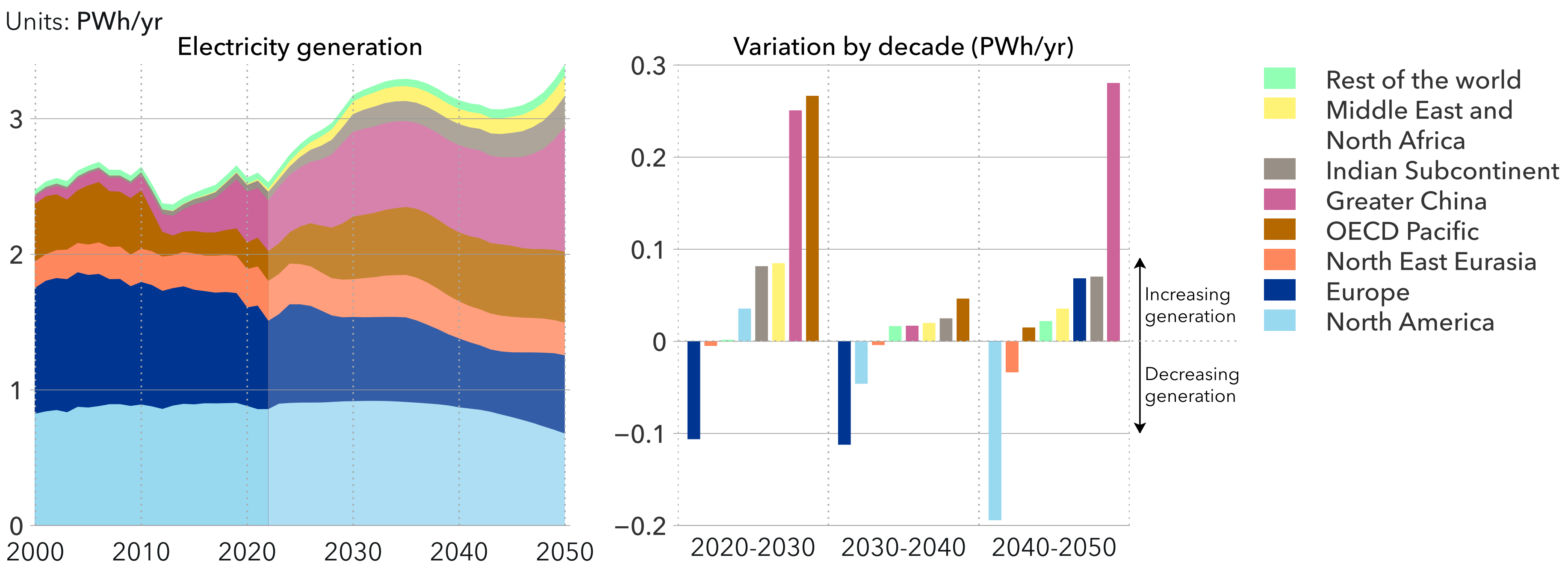
Electricity generation

Our Outlook reflects the renewed interest in nuclear energy sparked by energy security concerns, climate policies, and growing demand for electrification. We forecast nuclear energy output will have a stable 2% growth year-on-year from today's levels for the next 10 years (Figure 3.13). Output stabilizes in the mid-2030s before slightly declining in the mid-2040s. This is not due to reduction in new capacity, but rather because many older nuclear power plants will inevitably be decommissioned. From today towards 2030, most added capacity will be based on site-built, large-scale reactors that are already in the pipeline. Beyond 2030, additional capacity will most likely be a mix between site-built and factory manufactured SMR power plants. Nuclear energy output peaks at 3,400 TWh/yr by 2050, 30% higher than today.

North America, Europe, Greater China, and North East Eurasia are currently the top four nuclear energy regions. However, within a decade, Greater China's output will have grown to almost the same level as Europe and North America. Japan and South Korea will double their output from now to 2030 by bringing new capacity online and reopening currently dormant plants. South East Asia will add 34 TWh of nuclear by 2050, but with most of the growth starting only in the late 2030s. The Indian Subcontinent will see the biggest relative increase of all regions, growing from today's 55 TWh to 230 TWh by 2050, with almost 50 GW of installed capacity representing nearly 10% of the world nuclear fleet.

FIGURE 3.13

Nuclear power generation and evolution of generation by decade and region



Historical data source: IEA WEB (2024)

Capacity buildout and decommissioning

Several nations – including Bangladesh, Belarus, Turkey, Egypt, and the UAE – are beginning to embrace nuclear power with projects just commissioned or late in construction. Other countries – such as China, France, India, and the US – are adding new nuclear to their existing fleet. In our forecast, we have reviewed global nuclear plans and probability adjusted the capacity additions based on the status and timeline of the projects. In total, there is likely 82 GW of nuclear in the pipeline. In addition to those projects, we expect another 244 GW of additional nuclear power capacity to be added by 2050.

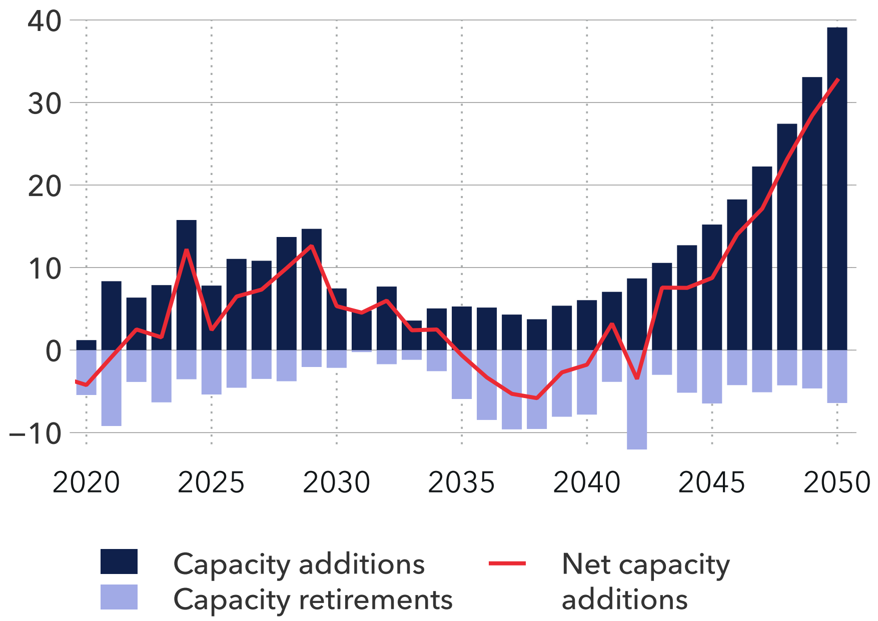
However, the future of global nuclear capacity largely hinges on the fate of existing power stations. Currently, half of the world's nuclear reactors are over 30 years old, with many nearing the end of their original design lifetimes. While some countries, like Germany, are moving forward with rapid decommissioning, others are reevaluating their strategies. The renewed emphasis on energy security, the high costs associated with decommissioning, and the relatively low expense of extending a nuclear plant's life have led some governments to consider upgrades and life-extension measures as a way to delay the retirement of these plants. However, at some point, these plants, at least in Europe, will be decommissioned as the expectations for newer, more safe designs as put forward in the EU Taxonomy shall be met.

For instance, Belgium and Spain have extended their decommissioning timelines from 2025 to 2035. Similarly, France and Sweden are postponing their decommissioning plans and actively engaging in plans to reinvigorating nuclear research and building new plants (Dalton, 2023), with declaration of intent to collaborate on nuclear (Messad, 2023). South Korea's president has vowed to reverse the country's phase-out plans, and Japan adopted a new policy in December 2022 to maximize the use of existing reactors by restarting as many as possible and extending their operating lives beyond the current limit. In our assessment, these moves indicate lifetime extensions for the global nuclear fleet. However, by the mid-2030s, the net capacity additions will be negative and the nuclear fleet will be contracting (Figure 3.14).

FIGURE 3.14

Nuclear additions and retirements

Units: GW/yr



An increased focus on energy security has prompted nations to reconsider their energy portfolios. Nuclear energy can provide a stable, domestic source of power. It is therefore an attractive option, but it could come at a higher cost than alternative energy options. In our model, regions dependent on energy imports and that already have existing nuclear energy are willing to support such local energy source.

Based on our model, we find that government support will make some regions willing to install more nuclear than they otherwise would have in the absence of the security concerns heightened by Russia's invasion of Ukraine. This applies particularly to regions dependent on energy imports and which already have existing nuclear energy installations. By 2050, North America, OECD Pacific, and the Indian Subcontinent together will install about 38 GW more nuclear capacity which will provide about 12 % more electricity. This is achieved by an additional support by governments and authorities in the range of 5% to 20% of the levelized cost of nuclear energy, from 2024 to 2050.

At the same time, Europe and Greater China will adopt an 'all available choices' approach. This means favouring power plants run with local resources or domestic technologies, with greater emphasis towards renewable technologies such as wind and solar. In the case of Greater China, this will be combined with large-scale battery expansion. As a result, energy security considerations will not lead to additional nuclear capacity build-out fuelled by energy security concerns.

The additional support governments are willing to give nuclear to secure energy supply is difficult to disentangle from other parameters affecting support for different power generation options – for example, the clean energy tax credit in North America that promotes all clean power options. For many countries, nuclear knowledge and overall infrastructure are important components of a nuclear military programme; in countries like the UK, France, and the US, nuclear support must be seen as a necessary piece of continued nuclear defence policies based on nuclear ships, submarines and weapons. It is also worth bearing in mind that it is not only nuclear contributing to secure energy, but renewable options as well. These other options also receive subsidy benefits from governments prioritizing local energy options. With this caveat, we find that energy security concerns will increase the total overall expenditure on nuclear by around 13% per year.

> The future of global nuclear capacity largely hinges on the fate of existing power stations. Currently, half of the world's nuclear reactors are over 30 years old, with many nearing the end of their original design lifetimes.

New capacity mix

SMR technology is increasingly praised as the next-generation technology that will take over the power sector. However, just like existing nuclear plant designs, SMRs need to demonstrate cost competitiveness, high safety levels, and solve non-proliferation and waste-management challenges. The APR-1400-based Barakah nuclear power plant in the United Arab Emirates may provide preliminary evidence of cost control and cost reductions achieved using standardized modules, but otherwise there is limited evidence to support claims that SMRs will solve the cost hurdle any time soon. Material use and labour cost per MW, and thus total cost, in SMRs increases the smaller a module gets (Stewart et al., 2024). However, government-financed projects could assume a lower discount rate than private investors, who perceive policy and technology risks, to make nuclear more competitive. Based on our assessment and assumptions, we find that it will be a long time before economies of mass production can outperform the scale economies of large, conventional nuclear installations.

New reactors are safer by design than previous generations of nuclear plants. They rely on more passive safety and having to comply with increasingly stricter regulations. However, new designs remain untested and the potential impact of SMR technologies on weapons proliferation is unclear. SMR technologies requiring higher-enriched uranium fuel could pose a greater proliferation risk than the 5%-enriched uranium used in today's power plants (Holt, 2017).

SMRs could, however, eventually make a valuable contribution to the decarbonization of hard-to- abate sectors like shipping, aviation and manufacturing. SMRs used for direct propulsion on ships offer a long-term energy solution compared to costly biofuels and e-fuels, but significant technological, commercial, and regulatory challenges means that we only include this option from 2045, but forecast nuclear to account for 6% of the maritime fuel mix by 2050.

SMRs are especially well-suited to compete in areas that are remote or unsuitable for large-scale renewables deployment as well as large sources of manufacturing demand such as steel, cement, and petrochemicals. These industries will need to secure a supply of electricity combined with heat – and possibly hydrogen – and could have the finances to develop SMRs but not a large-scale plant. In all these use cases, an SMR could support energy supply as a cheaper alternative to hydrogen derivatives or through flexibly supplying electricity to the grid or factory depending on the availability of cheap wind or solar energy. At other times, it could divert power to increase its production of hydrogen.

> SMRs are especially well-suited to compete in areas that are remote or unsuitable for large-scale renewable deployment as well as large sources of manufacturing demand such as steel, cement, and petrochemicals.

Small modular reactors (SMRs) added to the mix

SMRs are a design concept referring to the size, capacity, standardization, and modular manufacturing for in-factory mass production of nuclear reactors. They are small enough to be shipped to the plant site where several reactor modules can be integrated to the needed capacity and operated as a single system in a single housing. This production approach may reduce costs in the long run, but it will likely increase costs in the short term due to investment needs in manufacturing facilities, higher material intensity, and the time it takes for economies of mass production to make an impact. SMRs span a range of reactor technologies from proven light-water technologies to novel, untested technologies. Modern reactor technologies have passive safety systems and several new safety features that aim to improve safety.

Many countries and companies have submitted designs for approval with planned operational start-ups by 2030 at the earliest. However, only a few SMR designs have been approved by regulators so far in 2024. China and Russia are also developing designs, but it is uncertain whether those designs will be accepted elsewhere in the current geopolitical landscape.

In our model, we anticipate new nuclear capacity additions will be a mix between conventional large-scale nuclear power plants and SMRs. This mix will have large regional differences that depend on the regional starting points, existing nuclear programmes, building costs, and costs of capital. Assumptions about building times will also contribute to different end points in each region's capacity build-out.

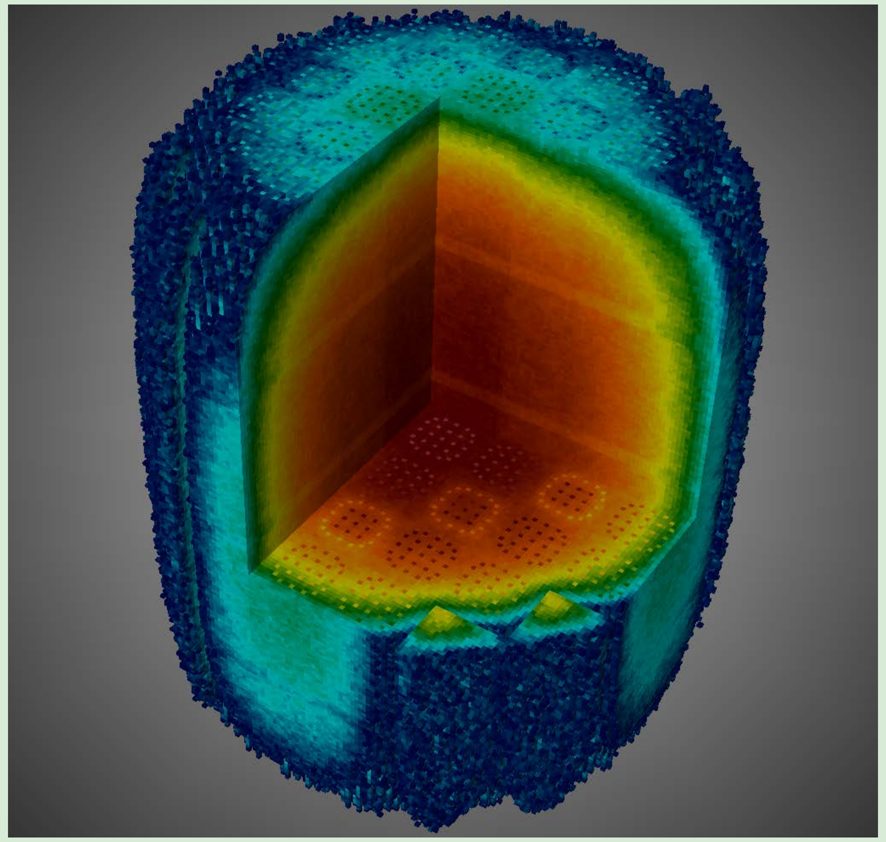
We have made an assessment based on the existing progress of SMR designs and a key assumption in our model is that learning rates are not uniform globally:

– North America, Europe, Japan, and South Korea will not accept any SMRs from Russia or Greater China.

– Similarly, we do not expect any SMRs from North America, Europe, Japan, or South Korea to be constructed in Russia or Greater China.

– For all other regions, we anticipate a 50:50 distribution of SMR construction from each bloc and learning rates will need to reflect an average of cost developments from both blocs.

Using available data for capacity additions post-2030, we have estimated fractional capacity (in MW) split between SMRs and conventional plants and assume this fraction will either increase or decrease depending on region going forward. We expect the initial costs of SMRs to be 60% above conventional large scale nuclear, but also a faster cost reduction of 10% for every doubling of capacity (Abou-Jaoude et al., 2023). Furthermore, we adjusted the construction time to account for the anticipated shorter building time for SMRs, starting with six years in 2030 and declining toward three years by 2050. Similarly, we used fixed build times for large scale nuclear between six and eight years in 2030 which decline to four years by 2050 in some regions.



SMR radiation simulation.
Image courtesy DOE - Exascale Computer Project/Flickr

The assumptions of capacity additions and reductions in cost combined with cost of capital gives the LCOE which determines the cost-effectiveness and appeal of power station investments (see Chapter 2 for more details on electricity supply). Based on our model, between 2030 and 2050, about 45%, or 230 GW, out of the total 500 GW nuclear capacity that have started construction will be based on SMRs. This will result in about 600 SMRs having started construction by 2050. However, two thirds of them will only start construction after 2045. As we assume OECD countries will not accept Russian or Chinese technology and vice versa, the cost learning rates – and thus 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. By 2040 regional weighted average costs will still be above the reference costs of 2030, and by 2050 costs will be up to 20% lower in several regions. So even if the cost reduction of SMRs can be up to 60% by 2050, the initial higher cost of SMRs cost combined with limited cost reductions of conventional nuclear means that the overall cost of new capacity will only be slightly lower than the cost of large scale nuclear in 2030. This is the main reason our forecast has limited uptake of nuclear in the energy mix. For comparison, solar+storage will see cost reductions in the range of 25% to 35% from today to 2050, and the largest reduction is happening within the next 10 years.

3.5 BIOENERGY

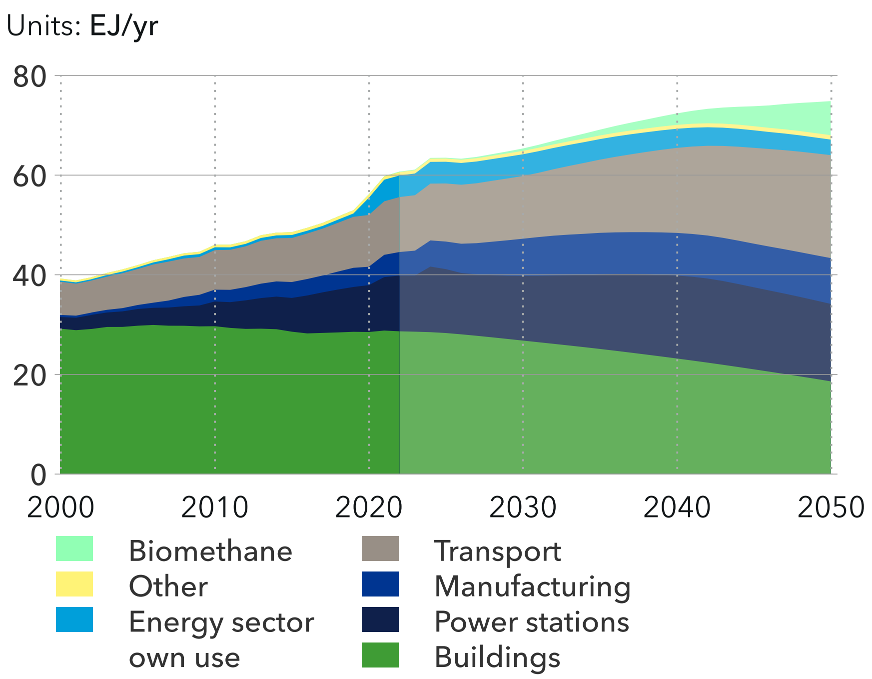
Bioenergy is the biggest renewable source of primary energy supply today. It encompasses all sources derived from biomass including organic waste, agricultural and livestock residues, forest wood, and energy crops. It will see limited growth in total volume but remain an important part of the energy supply with a 12% share of primary energy in 2050, higher than coal. We project that in the early 2040s, bioenergy, with its naturally limited energy potential, will be surpassed as the main renewable energy supply source by solar, which has almost unlimited potential.

Modern bioenergy will dominate the bioenergy demand mix
Between now and 2050, there will be significant developments in energy products from bioenergy resources and the energy demands that they cover. Total biomass demand (energy input before losses) will increase by 23% and see a big shift between sectors. Traditional use will decline sharply; our modelling shows a 35% reduction of biomass use in the buildings sector (Figure 3.15). This reduction is driven by electrification, ambitions to increase efficiency, and measures to promote clean cooking that reduce reliance on traditional biomass in low-income regions for space heating and cooking fuel. Nevertheless, it will be hard to replace the traditional uses completely, especially in Sub-Saharan Africa where the transition to clean cooking only keeps up with population growth (IEA, 2023a). The reduction in traditional use will reduce pressure on deforestation in vulnerable places and might also free up volumes to produce modern bioenergy in places where the biomass resource complies with sustainability criteria.

Modern bioenergy will see strong growth in both relative numbers and by redirecting traditional bioenergy volumes from traditional to modern use. Modern bioenergy includes higher-value energy

FIGURE 3.15

World bioenergy demand by sector



Historical data source: IEA WEB (2024)

products like biofuels, biochar, and electricity to cover demand in transport, manufacturing, and power.

Bioenergy demand in transport and manufacturing will almost double. This expansion will primarily be driven by decarbonization policies, including mandates, carbon pricing, and consumer-push, coupled with the limited availability of alternatives to liquid biofuels in aviation and maritime transport.

Currently, almost all bioenergy use in the transport sector is in road transport (94%), primarily in the form of blends with gasoline and diesel with a minimal amount in gaseous forms like biomethane. However, this landscape is shifting. We project bioenergy demand from road transport will reduce by 58% by 2050. This is driven by ongoing electrification efforts and less demand for blended fossil fuels. The trend is further supported by intensified competition for biomass sourcing for other transport sectors. By mid-century, aviation will take the biggest share of bioenergy for transport (48%), followed by maritime (32%). Aviation's higher share stems from decarbonization policies and consumer-push that has led many airlines to set tough targets for switching to sustainable aviation fuel (SAF). This is already visible in the market (Neste, 2024): SAF production doubled between 2022 and 2023 and will more than double again between 2023 and 2024, albeit from a very low starting volume (Beresnivicius, 2023).

Similar drivers will push the uptake of biogases in manufacturing. Biogases can meet high-temperature needs and substitute natural gas in industrial processes in hard-to-abate sectors like steel, cement, and chemicals. Biomethane production will meet 9% of bioenergy demand in 2050, and this energy carrier facilitates the uptake of energy with biomass origin in manufacturing.

Power stations are poised to increase their consumption of bioenergy by 38% between 2023 and 2050. This reflects, among other trends, coal-fired power plants increasingly integrating wood chips to curtail emissions and power generation utilizing biogas generated from waste. This leads to a steady growth of electricity generation to the early 2040s, with demand peaking at 17 EJ/yr. Thereafter, it will slowly lose position to other energy sources, especially wind and solar. This is most visible in the Indian Subcontinent and Greater China. Electricity generation has a 23% (16 EJ/yr) share of biomass demand in 2050.

Modern bioenergy will be based on sustainable raw materials

Sustainability criteria are crucial to ensure future expansion of biofuel production to meet decarbonization objectives without compromising the current biomass systems. As a result, expanded biofuel production will be based on biomass sources such as agricultural by-products, residues of forestry and wood industries, municipal waste, and industrial residues. There are significant concerns associated with direct and indirect land-use changes – converting natural vegetation to grow biofuel feedstock typically releases a large amount of carbon from soil and plant biomass. This creates a 'carbon debt' that can take years to repay.

The temporal perspective of biomass emissions is a crucial concern. In our projections, we account for these potential additional emissions – stemming from activities like deforestation to create space for crops intended for liquid biofuel production – within the category of agriculture, forestry, and other land-use (AFOLU) emissions. Sustainability and carbon footprint are important in assessing the suitability of different origins of biomass, and many parameters are relevant in these assessments (Royal Academy of Engineering, 2027). The additions and updates to the EU's *Renewable Energy Directive III* (RED III), in force since November 2023, show how these criteria are tightened to ensure emission-neutrality. Centralized utilization of biomass also opens possibilities for removal of emissions through bioenergy capture and storage (BECCS), which can also increase financial and environmental attractiveness of potential projects. Several initiatives are already underway on both sides of the Atlantic (Phillips et al., 2024).

Regional trends

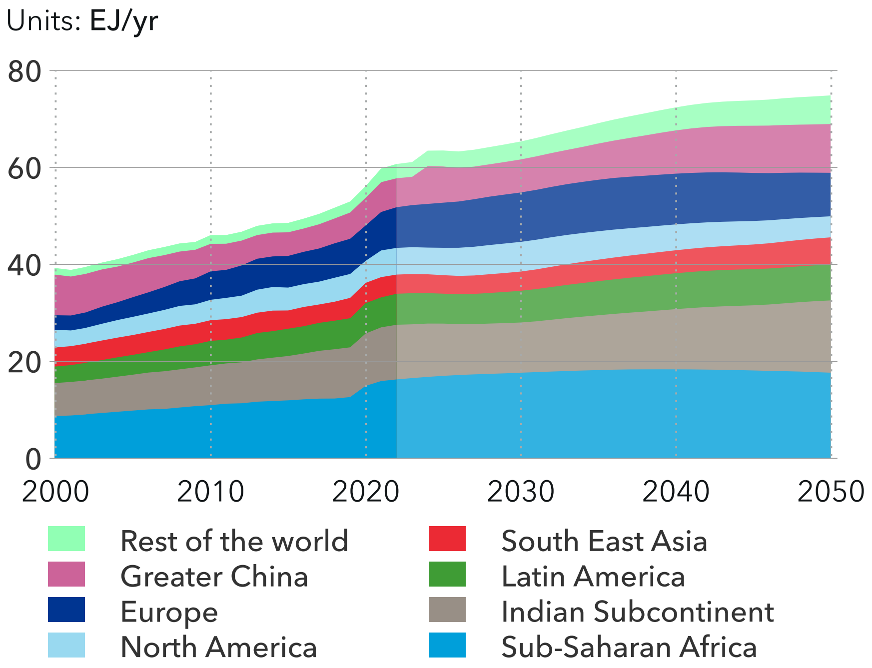
The distribution of demand will undergo only gradual change throughout the forecast period for most regions (Figure 3.16). Sub-Saharan Africa is poised to maintain its position as the largest global consumer of biomass with a stable share of around one quarter worldwide.

The Indian Subcontinent and Greater China each currently display high use of bioenergy and significant future growth. Use in the Indian Subcontinent rises 27%, with much of the increase due to more bioenergy demand in manufacturing. Use in Greater China grows 43%, with a particularly high share of the increase stemming from additional electricity generation.

Certain other regions will likely experience bigger relative increases in their utilization of bioenergy, notably the Middle East and North Africa which will triple from a low starting point. Latin America will increase its bioenergy activities less than the global growth rate, due to policy gaps and difficulties in meeting sustainability criteria for biofuel export. We expect both North America and Europe to experience a slight decline in bioenergy use.

FIGURE 3.16

Bioenergy demand by region



Historical data source: IEA WEB (2024)

Energy and emissions: the implications of dietary shifts

Global agriculture and food ('agrifood') systems are extensive value chains which have a substantial impact on energy and climate. IPCC (2019) estimates that global agrifood systems are responsible for 21% to 37% of global emissions due to land use, storage, transport, packaging, processing, retail, and consumption. This includes emissions from food loss and waste – it is estimated that one third of the food produced globally is wasted. Global agrifood systems have other significant environmental impacts. Agriculture accounts for around half of the world's habitable land and 70% of global freshwater withdrawals. Livestock makes up 94% of global mammalian biomass, excluding humans (Ritchie et al., 2022). Use of these resources also has a significant biodiversity impact (this is discussed further on page 81)

Demand for processed food drives energy use

Processing is a driver of energy use in food production. Processed food uses more energy than unprocessed or minimally processed foods. The Nova classification places food into four categories based on level of processing (FAO, 2019):

1. Unprocessed or minimally processed foods: e.g. fruits, seeds, roots, eggs, fungi, and algae.

2. Processed culinary ingredients: e.g. oils, butter, lard, sugar, and salt.

3. Processed foods, usually created by combining products from groups 1 and 2: e.g. canned legumes or vegetables in brine; some animal products like ham, bacon, smoked fish; most freshly baked bread; and some cheeses.

4. Ultra-processed foods, typically using industrial ingredients and techniques: e.g. carbonated soft drinks and energy drinks; confectionary; cookies, pastries, and cakes; and sausages, burgers, and hotdogs.

For example, one study compared the energy use of producing 1 kg of dairy products using milk (unprocessed food) as the baseline (Global Alliance for the Future of Food, 2023). It calculated that twice as much energy was needed to produce cheese (processed food) and up to 10 times as much to produce strawberry yoghurt (ultra-processed). Processed and ultra-processed food products are in great demand in high-income countries, and demand is starting to increase in middle- and low-income countries. Consumption of ultra-processed food products is a driver of energy use in food production and produces more emissions along agrifood system value chains.

Emissions intensity of diet linked to income

Income and subsequent purchasing power directly influence dietary intake. Global wealth and average purchasing power will likely increase through 2050, leading to increased overall demand for food and shifts in diets. Demand for processed food – and for other protein sources like meat, dairy, and fish – will increase with income, which in turn adds pressure on resources needed for agrifood systems (e.g. land, water, and energy).

The GHG emissions intensity of food products varies hugely. Plant-based products like fruits, vegetables, grains, and nuts typically produce less than 3 $kgCO_2$ per kilogram of food. Animal products like beef, lamb, mutton, and cheese produce significantly more, ranging from 20 to 60 $kgCO_2$ per kilogram of food (Ritchie et al., 2022). The vast majority of emissions come from land-use changes (biomass changes from deforestation to make way for farmland and pastures, and changes to soil carbon) and farm emissions (methane emissions from livestock and emissions from fertilizers and farm machinery). Emissions in agrifood systems are concentrated in these earlier stages of production, with the later stages of processing, transport, retail, and packaging producing comparatively few emissions. A notable exception is air-freighted import of food, which substantially increases the otherwise low-emissions of, for example, seafood products. Salmon produced in traditional open net pen systems in Norway produces around 3.4 $kgCO_2$ per kilogram of food, which is tripled when the salmon is air-freighted to the US. An in-depth analysis of seafood systems can be found in DNV's *Seafood Forecast* (2024).

> Understanding the role that agrifood systems play in the energy transition will be crucial for many countries globally.

Growing demand for meat is driving agrifood emissions

Meat consumption exemplifies the relationship between income and emissions intensity of diet. Producing meat is emissions intensive, especially beef due to the high output of methane by cows, the demand for feed, and the land use required for grazing. People in low-income regions currently consume the least amount of meat, but as income increases, so does overall consumption of meat. Analyses show that most low- and middle-income regions, where increased purchasing power is a main factor for shifting diets, have growing meat consumption rates (Serraj and Pingali, 2019).

High-income regions currently consume the most meat and have high-protein diets, resulting in diets with the highest emissions globally. However, there is evidence that suggests some high-income countries are approaching the point at which an increase in income does not lead to a further increase in meat consumption (Whitton et al., 2021). Canada, New Zealand, and Switzerland have likely reached ‘peak meat’, where meat consumption decreased while GDP increased from previous years. Concern regarding the environmental impact of meat production is cited as a major reason for this dietary shift. Other explanations for behavioural changes leading to low- or no-meat diets include health considerations, changing cultural norms, animal welfare concerns, and increased availability of alternative proteins.

Table 3.2 shows possible dietary shifts in the 10 ETO regions to 2050, based primarily on research of past dietary trends by Sikorski et al. (2023), supplemented by various other literature and data sources. The regions are split into high-, middle-, and low-income groups.

Agrifood systems in the energy transition

Global agrifood systems are intertwined with the global energy system. Understanding the role that agrifood systems play in the energy transition will be crucial for many countries globally, given the IPCC view that these systems account for around one quarter to one third of global emissions. This vital interaction between agrifood systems, energy, and climate is becoming increasingly recognized on the global stage. At COP28, 160 world leaders endorsed the *Agriculture, Food, and Climate Action Declaration* which committed USD 2.5bn in funding to support food security and access, sustainable agriculture, and climate action measures.

Governments are introducing policies and investment targeting emissions in agrifood systems. Examples include the EU’s *Farm to Fork Strategy*, Japan’s *MIDORI Strategy for Sustainable Food Systems*, Brazil’s *Low-Carbon Agriculture Plan*, and Denmark’s recently proposed tax on agriculture emissions targeting livestock, fertilizer, and forestry – which would be a world-first (Dwyer and Quiroz, 2024). Although we do not directly implement specific agrifood factors into our analysis, we expect initiatives and regulatory efforts to deepen as agrifood systems become increasingly present in the energy transition space. We will monitor these developments in future Outlooks.

TABLE 3.2
Possible dietary shifts to 2050

Grouping	High-income	Middle-income	Low-income
Regions in group	Europe, North America, and OECD Pacific	Latin America, North East Eurasia, the Middle East and North Africa, Greater China, and South East Asia	Sub-Saharan Africa and the Indian Subcontinent
Possible trend to 2050	– Increased consumption of more sustainable and diverse food sources, including plant-based proteins (EUR, NAM, OPA) – Some decrease in red meat and increase in poultry consumption (EUR, NAM) – Increased consumption of seafood (OPA) – Increased consumption of dairy (EUR, OPA) – Health becomes an increasingly higher priority for diet choices (EUR, NAM, OPA)	– Increased consumption of meat, typically pork or beef (LAM, NEE, MEA, CHN, SEA) – Consumption of grains like rice, wheat, and cereals is stable in some regions (LAM, NEE, CHN) and decreased in others (MEA, SEA) – Increased consumption of dairy and eggs (LAM, NEE, MEA, SEA) – Increased consumption of seafood (SEA)	– Overall increased demand for food (SSA, IND) – Continuation of plant-based diets focused on fruit, vegetables, and cereals like rice (IND) – Some regionalized increased consumption of food with higher fat and sugar content, and some meat and fish (IND) – Increased consumption of meat in urban populations, continuation of plant-based diets in rural populations (SSA)

3.6 OTHER ENERGY

Other renewable energy sources are likely to remain marginal on a global scale between now and 2050. We look at five main ones here: solar thermal, concentrated solar power (CSP), geothermal, nuclear fusion, and ocean energy. Of these five we model solar thermal and geothermal, which combined will provide less than 2% of world primary energy by mid-century. Concentrated solar power is not yet large scale and we do not see it scaling during the forecast period. Nuclear fusion is exciting and may have a large potential and has seen a recent increase in funding, but similar to all new energy sources, fusion must first work at industrial scale and compete with growth from existing energy sources. Finally, ocean energy will be limited to niche applications.

In this Outlook, **solar thermal** refers to heat generated in solar water heaters. Globally, primary energy supply from solar thermal energy will decline from 1.8 EJ in 2023 to 0.4 EJ in 2050. Around 82% of this energy heats buildings and will mainly be used in China. This region will also be responsible for most of the decline in solar thermal as heating water from electricity takes over. Section 1.3 discusses how buildings use energy for heating water in more detail.

CSP, though not modelled, is another technology which is not yet large-scale. This technology concentrates a large area of sunlight onto a receiver, generating both heat and electricity. While this improves the efficiency of power generation, it adds additional manufacturing complexity and cost. This complexity has hindered the roll-out of CSP technology, and well publicized failures, such as at the Crescent Dunes facility in the US, have eroded faith in it. Two types of CSP plants exist, either parabolic trough power plants or molten-salt tower / central receiver power plants. Both technologies still need to mature. China currently leads the way in CSP installations, announcing new installations in 2022 and 2023 which will bring the country's capacity to 3 GW. Spain also has a modest amount of CSP (around 2.3 GW), though the largest CSP installation today is the Noor Power Station in Morocco. Despite LCOEs starting to become low enough to be competitive with other renewable technologies, we do not see this technology reaching a large-scale buildout during the forecast period.

Geothermal technology extracts the heat found under the surface of the earth and uses it either directly for heating and cooling or converts it into electricity. Lower temperatures can be used for heating and cooling, but electricity generation requires high temperature resources – a minimum of 150°C. Historically, the need for high temperatures has limited the areas where geothermal energy can be used for electricity generation to tectonically active regions where water or steam is close to the surface in natural reservoirs. New enhanced geothermal systems (EGS) can create artificial reservoirs by pumping water and other fluids to fracture rocks, allowing for energy extraction from areas which were not previously considered commercially viable. Geothermal technology is also being used in ground source heat pumps to cool and heat buildings, with no high temperature resources needed.

As geothermal energy is a stable source of renewable energy – in contrast to variable solar and wind power – with high-capacity factors, it is seen as a solution to fill any supply gaps caused by variable renewables. With the growth of AI and its electricity needs – both for processing data and cooling data centres – Amazon, Google, and Microsoft have all begun working with geothermal and nuclear companies to produce carbon free electricity to run their data centres and reduce greenhouse gas emissions from their operations. The largest barriers to the widescale implementation of geothermal today are the high upfront capital expenditures, long project development timelines, and higher risks during initial phases of exploration. All of these lead to challenges in financing projects. With large companies now taking an interest in the development of this technology on a wider scale, it is possible these barriers will lessen with time.

As of 2023, geothermal energy provided 4.0 EJ (0.6%) of the world's primary energy supply. By 2050, this will rise to 8.5 EJ (1.3%). Worldwide, geothermal energy is overwhelmingly used by power stations, with the exception of Greater China, where the demand comes mostly from buildings. South East Asia and OECD Pacific will lead the world in geothermal energy in 2050 with it making up around 5% and 3% of these regions' primary energy mixes respectively.

Ocean energy is another technology that we do not expect to scale. There are several types of ocean energy, including tidal barrage energy, tidal stream energy, wave energy, ocean thermal energy conversion (OTEC), and marine current power. Of these, the first three are the most highly developed today, with a 2020 installed capacity of 521 MW tidal barrage, 10.6 MW tidal stream, and 2.31 MW wave power generation capacity. The LCOEs of these technologies, and the investment costs, are declining but remain higher than for other forms of renewable energy. Another barrier to their large-scale implementation is limited suitable locations, often far from an existing grid with accordingly high grid-connection costs. There is also concern about the environmental impact of these structures, including noise, risk of

collision with marine animals, and changes to water flow and quality.

Despite these hurdles, there are plans for new tidal stream installations, the largest being the four-phase MeyGen project in Scotland. Situated between the Scottish mainland and the Island of Stroma, the site has ideal depth, water flows, and proximity to the mainland. Phase one comprises of four 1.5 MW turbines and has been operational since March 2018. It has generated 51 GWh as of March 2023. There are proposals for other tidal projects in the UK in East Anglia and on the river Mersey, and the EU currently has 17 major projects in progress, with over 160 MW of capacity. In the future, it looks like ocean energy technologies will be suited to niche markets – for example small island developing states where it would be most costly to import energy – or coupled to provide another operation with power – such as oil and gas platforms or aquaculture operations. In other cases, ocean energy could be used directly rather than converted to electricity first to avoid additional cost and componentry, for example wave-powered desalination (Maksumic, 2024).

Nuclear fusion has long been hailed as the holy grail of clean energy, offering the promise of virtually limitless power without carbon emissions. The recent breakthroughs in fusion technology, particularly the December 2022 experiment at the Lawrence Livermore National Laboratory (Ahire, 2023), marked a historic milestone where more energy was produced than was consumed in the reaction. This achievement has rekindled optimism about the potential of fusion to transform global energy markets. However, significant technical and engineering challenges remain before fusion becomes a viable and scalable energy source. Private companies, such as Commonwealth Fusion Systems, have taken the lead with innovative designs like using superconductors to create the magnetic fields necessary for fusion reactions (Temple, 2022). Others, like TAE technologies (2024) or Helion (Temple, 2023), focus on extreme high temperatures that combine magnetic fields and plasma inertia to achieve fusion conditions. These companies are targeting the late-2020s and early 2030s to bring commercial reactors online.

In recent years, fusion has seen substantial financial backing, indicating a growing belief in its long-term viability. By early 2023, cumulative investment in fusion research had reached approximately USD 6.2bn, driven by private sector interest (Wesoff, 2024). Many of the start-ups have achieved key technological milestones that further bolster confidence in the sector. The rising interest is driven by the need for alternative, scalable, and clean energy sources to combat climate change. However, while fusion offers enormous potential, experts remain cautious about its timeline for commercialization, stressing that it will take time to reach the scale necessary to impact global energy grids. Until then, more immediate technologies like solar PV, wind, and traditional nuclear fission will continue to dominate clean energy expansion.

How the global energy transition is reshaping jobs and skills

The energy transition involves a huge economic and employment shake-up which will, like other major shifts, result in jobs being created, eliminated, replaced, and transformed. The global energy transition will affect a labour force of millions of people around the world and the number of 'green' jobs – jobs connected to the wider renewable energy value chains – will greatly increase. Two salient questions arise: how many jobs will the energy transition create and where will those jobs be?

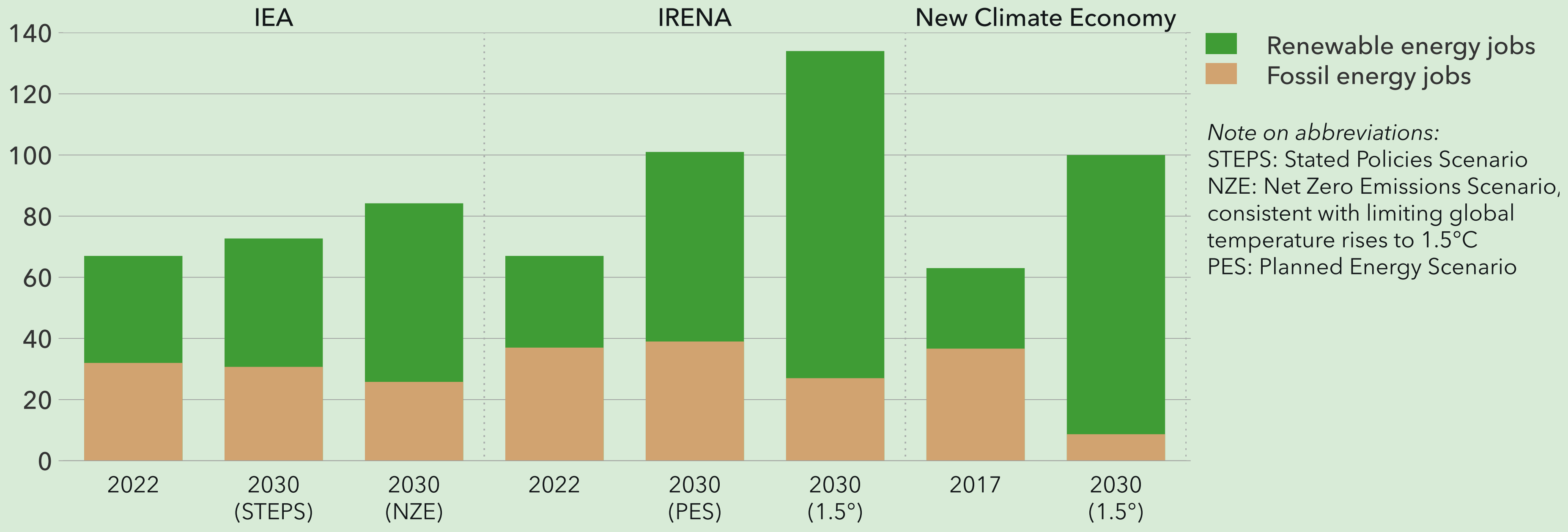
Major studies yield different estimates due to job categorization

Several analyses have endeavoured to quantify the number of jobs created by the energy transition. The consensus is that there will be a net increase of energy jobs, despite job losses in 'traditional' or 'brown' energy sectors like fossil-fuel extraction, fossil fuel-based electricity generation, and petroleum refining. There is large variation in estimates of net job additions in studies by major international institutions due to the variety of job categorizations, scenarios, and quantification methodology (Figure 3.17).

FIGURE 3.17

Global energy employment estimates from selected studies

Units: Million workers



Note on abbreviations:
STEPS: Stated Policies Scenario
NZE: Net Zero Emissions Scenario, consistent with limiting global temperature rises to 1.5°C
PES: Planned Energy Scenario

Data source: IEA (2023), IRENA (2023), IRENA and ILO (2023), New Climate Economy (2018)

Scenarios which forecast a future that is consistent with limiting the global temperature increase to 1.5°C estimate much higher growth in green jobs than less ambitious energy transition scenarios. Nonetheless, there is still large variation between forecasts for the same overarching temperature threshold, ranging from IEA's (2023) *Net Zero Emissions Scenario* estimate of 84 million total energy jobs to IRENA's (2023) *1.5°C Scenario* estimate of 134 million total energy jobs. Our review of academic literature produced a similar variation of estimates which are highly dependent on job categorization and energy transition scenario.

Typically, energy jobs are categorized into 'direct' and 'indirect' jobs. Direct jobs are created for the design, manufacture and construction, installation, operation, and maintenance of energy facilities. These include jobs like solar panel installation or pipeline engineering. Conversely, indirect jobs include those generated in the whole supply chain to support the energy facilities, such as steel manufacturing used in wind turbine construction or energy research institutions (RMI, 2023). Setting the boundary for job implications of the transition is a key issue. For example, the study by WRI (Saha et al., 2022) estimates a net increase of 6.4 million jobs from 2020 to 2035 in the US under a net-zero scenario. This estimate includes 'induced' job creation when wealth generated directly or indirectly from the energy industry is spent in the wider economy. Studies presenting job estimates vary in their use of narrow or wide definitions, illustrating the difficulty in accurately forecasting job creation or losses.

Changes to the energy labour mix are already noticeable

IRENA and ILO (2023) estimated that renewable energy alone already employed around 13.7 million workers in direct and indirect jobs globally in 2022, up from 12.7 million in 2021. Additionally, the IEA (2023b) estimated that the total number of green jobs was greater than traditional energy jobs for the first time ever in 2021 and overall energy employment growth in 2022 and 2023 was entirely due to green energy jobs. Furthermore, investments in renewables generate three times more jobs per dollar than investments in the fossil fuel industry (UN, 2022).

Renewable power generation from solar is expected to be the biggest growth sector. China currently has the largest energy workforce and will see the largest net increase in jobs. In traditional energy, coal, oil, and gas supply are slated to experience the largest direct job losses while indirect jobs in the internal combustion engine (ICE) vehicle sector will see the largest decrease. Strong growth in green energy is partially due to more labour-intensive value chains than traditional energy, leading to higher estimates of green employment (Ram et al., 2022).

The energy transition will see many existing occupations incorporate green functions and skills, some traditional jobs transition into green ones, and the transformation of some non-green 'neutral' jobs into indirect green jobs (Economist Impact and Iberdrola, 2024). For example, integration of green skills into existing work like plumbers working with heat pumps or accountants working with renewable energy finance can be categorized as green jobs. The Economic Impact (2023) definition of green skills as '… the knowledge, abilities, values and attitudes that are needed to support sustainable and resource-efficient business operations', captures this redirect in existing operations.

Skills: the necessary transition lever

The demand for skilled workers is increasing because green jobs typically have higher skill requirements than traditional energy jobs. A competent workforce is a precondition for a successful energy transition in all Outlook regions. However, the opportunity for a worker to gain skills, both in terms of formal education and on the job training and certification, is linked to socio-economic factors where high-income regions have greater access than low-income regions. Without policy support, dialogue with workers, and adequate investment in training and skills programmes, workers in underprivileged areas are vulnerable to job insecurity and are at risk of being left behind in the energy transition. We explore issues of justice and fairness arising from the energy transition further in the just transition fact box (see Page 127 in Chapter 5).

The strong demand for skilled workers is also relevant in middle- and high-income regions. Employers in these regions face a shortage of skilled workers in areas ranging from formal technical education, like engineers and data scientists, to skilled trades, like electricians and carpenters. Although many skilled workers in existing traditional energy jobs have the necessary competencies to transition to green jobs given time and investment, there is still a skills gap. Continued investment in fossil-fuels can create a talent lock-in and affects education opportunities for green energy; universities globally still produce more graduates for fossil-fuel sectors than for renewable energy sectors (Vakulchuk and Overland, 2024). Skills gaps across the green energy value chain threaten to limit the pace of the global energy transition but will affect regions differently (IEA, 2023b). This is exemplified in the case study example below.

Transition dynamics and jobs: the cases of Australia and India

The energy transition is highly context dependent and will change the employment mix in every country differently. For example, the two geographically large and resource rich countries of Australia and India will experience vastly different job landscape changes due to contextual differences. Australia is a high-income country with developed tertiary economic sectors, an efficient fossil fuel sector, and skilled labour force. Conversely, India is a low-income country that relies heavily on primary sectors like agriculture, a coal focused fossil fuel industry, and a labour force engaged in primarily informal work. Table 3.3 compares labour force and economic sector data of Australia and India from 2023, showcasing how different the labour markets are (ILOSTAT, 2024).

Over the past few years, both countries experienced net growth in energy employment. The change in Australia's energy workforce has already been consistent with global consensus of future changes, comprising losses in traditional fossil fuel sectors and gains in green energy sectors. In a net-zero scenario, we forecast Australia will continue this trend of growth in green energy jobs and decrease in traditional energy jobs; an estimated 3% to 4% of the total workforce will be engaged in the energy sector in 2060, up from less than 1% in 2020 (McCoy et al., 2024). This estimated growth is complemented by an existing suite of programmes and initiatives to support workers reskilling and transitioning away from fossil fuel sector jobs. However, the distribution of jobs will remain uneven throughout the country and impacts on fossil-fuel dependent communities will need to be addressed.

TABLE 3.3

Labour force and economic sector data in Australia and India

Parameter	Australia	India
Labour force participation rate (%)[1]	66.9	55.8
Share of informal employment (%)[2]	26.1	88.8
Share with advanced education (%)	47	13.4
Share of agriculture (%)	2.8	43.5
Share of industry (%)	19.2	25
Share of services (%)	78	31.5

[1] The global estimate for labour force participation rate is 60% in 2024.

[2] The global estimate for informal employment is 57.8% in 2024.

India represents a unique case in that energy employment has grown in both traditional energy and green energy sectors since 2019. This is partially due to efficiency; in India, ten times as many workers are required to produce a tonne of coal than in Australia (IEA, 2023b). Additionally, India's decarbonization pathway will be slower and have a later phaseout of coal due to prioritization of development, poverty alleviation, and infrastructure creation. In a net-zero scenario, we forecast India will continue its strong growth in green energy jobs, creating up to 35 million green jobs by 2047 (Sattva Consulting et al., 2023). Conversely, around 74,000 formal, direct coal mining jobs will disappear by 2050. This does not include job losses from any specific coal phase out goals or the slew of informal and indirect jobs that may also be lost (Global Energy Monitor, 2023).

Much of the created green energy workforce will remain informally employed, leaving many workers facing insecure work conditions. India's workforce will become more skilled, with a growing number of graduates with tertiary education and increased access to training and certification programmes. This workforce skilling is supported by the Skills Council for Green Jobs (SCGJ), an initiative launched by the government of India to promote and implement skills development and industrial-relevant training for green energy sectors. However, support for education and skills must be strengthened to meet India's climate and energy ambitions.

Jobs and skills in the ETO model

The shift in skills, education, and jobs are tightly linked with socio-economic and energy changes, and thus we must assess these topics in tandem. In our analysis, we do not model jobs or employment. Instead, we include jobs and skills in our analysis by considering how it affects the speed of the energy transition. This includes aspects like how skills shortages may affect buildout time, cost, and risk; how shifts in the global labour market may affect energy supply-chain issues; and how workers and communities are affected, which affects the acceptance of the energy transition.

The labour market changes will have an important social and economic impact that affects millions of workers. However, quantifying the effect of the energy transition on energy employment is challenging. It is an area that DNV intends to research more intensively, especially at national level when we produce forecasts on the energy transition for individual countries.

4

FOSSIL FUEL

Highlights

This chapter details the transition happening in fossil energy sources and finds the current 80% fossil share of primary energy shrinking to about 50% by 2050.

The chapter accounts for sectoral demand, regional consumption and production across geographies. The Middle East and North Africa region will increasingly dominate oil and gas production and exports.

Dynamics in each category of fossil energy sources – coal, oil and natural gas – and investment projections are presented, finding that natural gas will be the largest of all single energy sources by 2050.

The energy sector's own use of fossil energy is accounted for together with a discussion of Scope 3 emissions. Fossil-fuel use for non-energy purposes (feedstock) is detailed and sees more stable demand over the forecast period.

Changes in the primary energy supply mix from all energy sources are summarized together with an overview of energy flows contrasting 2023 and 2050.

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4 FOSSIL FUEL

Fossil fuel currently accounts for 80% of the global primary energy supply. This share has been stable for several decades but is set for a dramatic change as renewable energy rapidly grows to take its place. We forecast that the share of fossil fuels will shrink by more than one percentage point per year to 50% by mid-century.

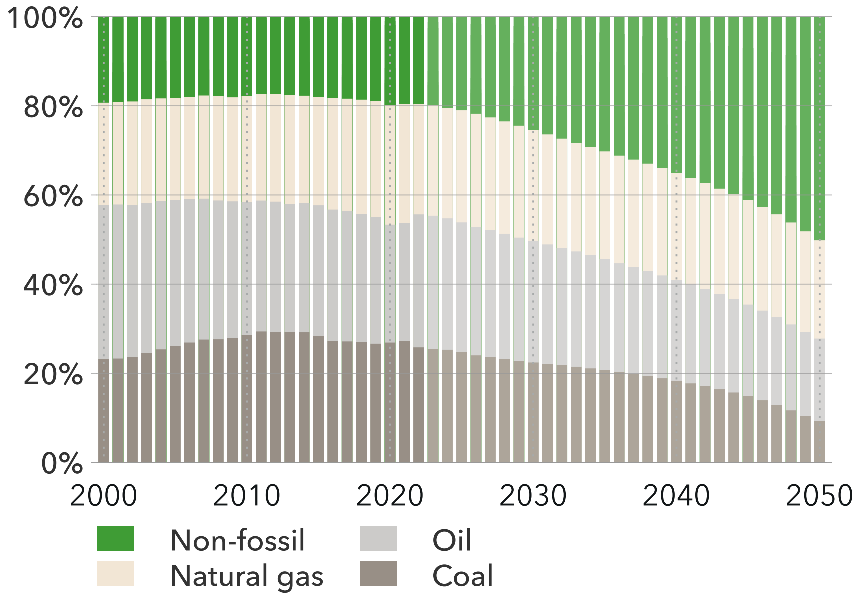
Over the coming decades, we will see a gradual phase-down of fossil fuels. This will begin with coal, which has the highest carbon footprint, followed by oil. Peak natural gas will come a little later and will be followed by a gentler decline such that gas maintains a high share of the primary energy supply mix throughout our forecast period. Even though renewables are already competitive with fossil-fired electricity in most places, we forecast that it will be many years – well beyond our forecast period – before low- and zero-carbon energy sources dislodge fossil fuels from the broader energy system (Figure 4.1).

While their share ebbs in the energy mix, we predict fossil fuels will retain most of their share in non-energy uses. 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 2050, the non-energy share will grow. Chapter 1.4 describes feedstock in more detail.

FIGURE 4.1

Fossil versus non-fossil in primary energy supply

Units: Percentages



Historical data source: IEA WEB (2024)

> It will be many years – beyond our forecast period – before fossil fuels are dislodged from the broader energy system.

4.1 COAL

Annual global coal demand experienced a rapid surge from 4.7 Gt in 2000 to its pinnacle at 8 Gt in 2014; since then, its use has fallen steadily. The economic and trade contractions resulting from the COVID-19 pandemic caused a 7% reduction in coal demand in 2020. Although coal has partially recovered, it will never reclaim its previous peak, instead dwindling to nearly one third of its present level by 2050.

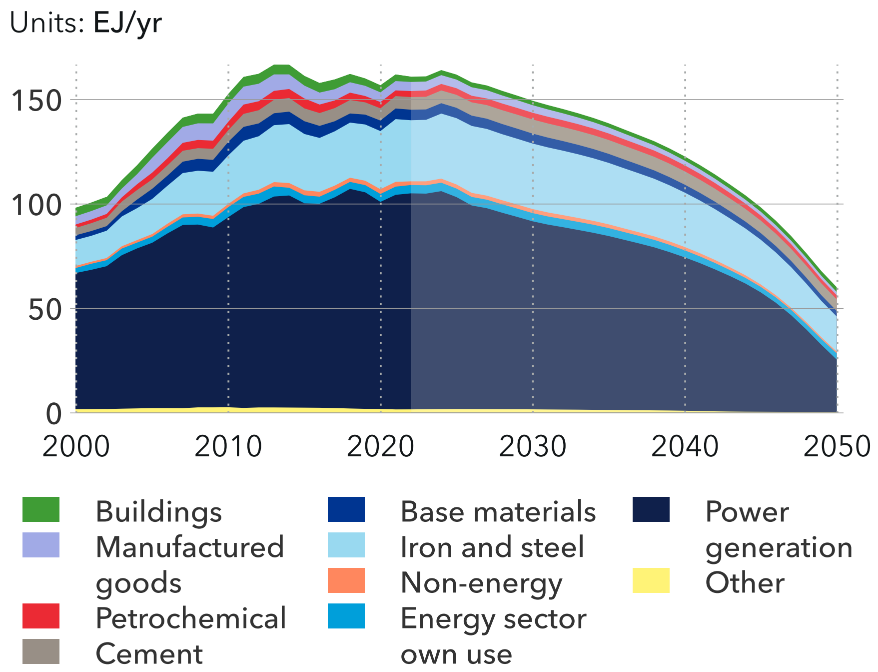
Coal production and use has fluctuated over the past 25 years. Annual global coal demand surged from 4.7 Gt in 2000 to 8 Gt in 2014. Following this, demand fluctuated before reaching a peak of 8.7 Gt in 2023, an increase of 2.6% from 2022. The increase in 2023, was primarily driven by growth in coal demand in China (+2.9%), India (+8%), and other Asian countries, which collectively exceeded the sum of demand declines in advanced economies like the US (-17%) and the EU (-23%). China's significant share of the coal market, at some 55%, gives it an outsized role in the overall global trend. We forecast that coal demand in China will remain at high levels, with a marginal increase in 2024, but will peak in 2025 before beginning to decline significantly. Global coal demand will follow developments in China, maintaining high levels with limited growth until 2025 before declining to 2.7 Gt by mid-century.

Sectoral demand

Coal has historically served as an economical and reliable source of thermal energy, making it the preferred heat source across various sectors (Figure 4.2). Power generation is the primary driver of coal demand, accounting for nearly two-thirds (64%) of coal consumption in 2023. Beyond power production, coal is vital for generating heat in manufacturing, and acts as a carbon feedstock for reducing iron ore in steel production. There are significant challenges to finding suitable and affordable substitutes for coal in high-temperature processes like cement, iron, and steel production. As a result, many industries remain reliant on coal despite its substantial carbon emissions.

FIGURE 4.2

World coal demand by sector



Historical data source: IEA WEB (2024), US DOE (2010), Heat Roadmap Europe (2015)

However, technological advancements and developments in blue and green hydrogen are challenging coal's dominance across sectors. For high-heat processes, we expect coal demand to slightly increase in the short term but decline rapidly after 2030. In the iron and steel sector, global coal demand will drop by nearly a fifth by 2050. Electricity will gradually replace coal for low-heat manufacturing processes to address local pollution issues. Gas boilers and electricity will facilitate a gradual reduction in coal use for most industrial heating needs.

Regional demand

Many regions have started to reduce their dependence on coal as the primary source of power generation.

Europe has been leading this trend. From 2022 to 2023, European coal demand declined by 20% to 344 Mt, driven by policy shifts and increased renewable energy generation. European coal imports decreased by 30%, falling to 89 Mt in 2023 from a surge of 128 Mt in 2022. This decline was largely influenced by reduced reliance on Russian coal due to geopolitical tensions and increased adoption of renewable energy sources. Similarly, in North America, climate policies and a declining reliance on coal for power generation as natural gas becomes more dominant, led to a reduction in coal demand by 10% from 2022, bringing the total down to 419 million tonnes in 2023. We forecast coal demand in Europe and North America to sharply decline to 163 Mt/yr and 170 Mt/yr respectively by 2030, with further decreases to around 25 Mt/yr in each region by 2050. Even coal-rich OECD Pacific regions will see a substantial 80% decline in coal consumption.

China's rapid expansion of wind and solar energy was not able to close the energy gap in the wake of the pandemic recovery and drought conditions that lowered hydropower availability. As the world's largest producer, importer, and consumer of coal increased its coal usage in 2023 to make up the difference, with growth in both power (8%) and non-power (2.5%) sectors that reached a combined total of 4,883 Mt. However, we expect the demand in China's power sector to grow by less than 1% in 2024 and forecast that by 2050, coal demand will fall to 20% of current levels, with an 83% reduction in the power sector and a 61% in manufacturing.

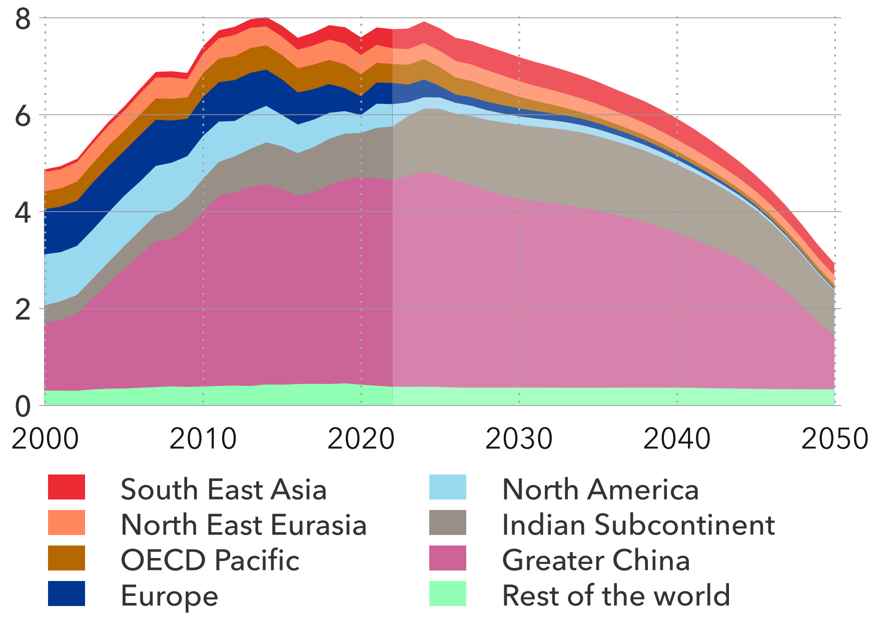
India is the second-largest regional contributor to global coal consumption growth. Unlike many parts of the world, India's growth in renewable energy sources has not kept pace with its rising power demand. The country's focus on infrastructure has also increased the consumption of cement and steel, which are typically produced using coal. As a result, India's total coal consumption reached 1,251 Mt in 2023, a 9% increase from the previous year. We project the Indian Subcontinent will see a 30% increase in coal demand by 2035 before it begins to decline towards mid-century.

Competition from natural gas and renewables is driving down coal use in OECD countries, but it will expand in many developing nations. Beyond 2030, stricter emissions regulations, increased competition from renewables, and advancements in energy storage and flexibility technologies will make renewables more dispatchable, diminishing the competitive position of fossil fuels, particularly coal. Consequently, new coal capacity additions will dwindle, retirements will rise, and capacity utilization will decrease. This pattern aligns with the coal 'death spiral' feedback loop: as coal plant utilization declines, its cost per unit of power increases, further eroding its competitiveness, making coal-generated power less economically viable, and reducing its use. Figure 4.3 shows coal demand in the different regions.

FIGURE 4.3

Coal demand by region

Units: Gt/yr



Historical data source: IEA WEB (2024)

Production and trade

Global coal production reached an all-time high of 8,970 Mt in 2023. Considerable production growth by the three largest coal producers – China (3.4%), India (12%), and Indonesia (13%) – saw those producers account for 70% of global output.

Most brown coal and a substantial portion of hard coal are consumed within their respective producing regions. Only four of our ten regions are net importers of coal: Europe, Greater China, the Indian Subcontinent, and the Middle East and North Africa. Efforts by Europe, Japan, and South Korea to decrease coal imports have been eclipsed by the unprecedented growth of imports in India, South East Asia, and China in 2023, with China alone increasing imports to 475 Mt.

Despite these local increases, the gradual long-term phase-out of coal-fired power plants in China, and reduced coal use in manufacturing, will progressively diminish its coal demand. The Indian Subcontinent, driven by India's efforts to enhance self-sufficiency, will reduce its reliance on imported coal. Major coal-exporting countries like Australia, Indonesia, Russia, and South Africa will continue as exporters, but their export volumes will decrease throughout the forecast period.

4.2 OIL

Oil has been the largest contributor to the energy supply since surpassing coal in 1964. The share of oil in the primary energy supply has been around 30% over the last decade and will remain so until 2027 before gradually declining to 18% in 2050.

Global crude oil demand increased by 1% from 2022 to 2023, reaching 89 Mb/d. This rise was driven primarily by robust demand in regions like Greater China, Indian Subcontinent, and the Middle East and North Africa, which offsets weaker demand growth in the OECD countries.

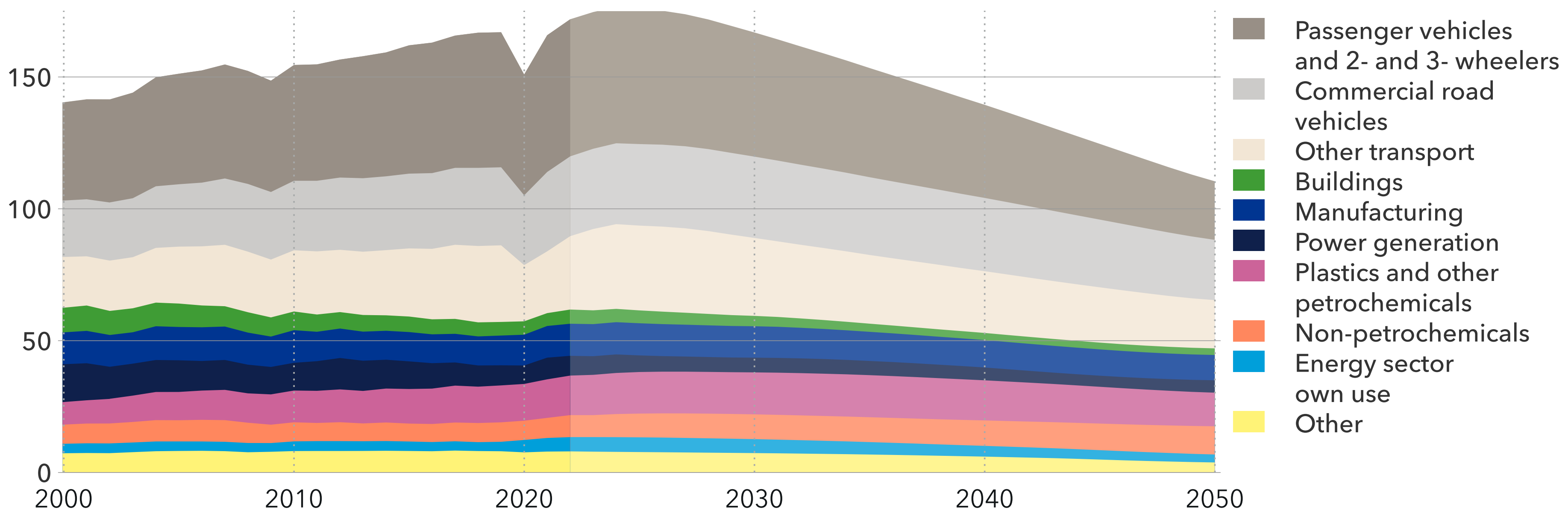
Sectoral demand

The transport sector, with its ever-increasing expansion due to population and economic growth, has been the main driver of increasing oil demand. Transportation's demand for oil has been steadily rising by about 1% per year for decades despite temporary dips like those in 2008 and 2020, and oil's share of energy demand in the transport sector has been around 70% since 2017 (except in 2020). Due to EV sales gaining momentum and the ongoing build-out of non-fossil electricity generation capacity, we expect this trend to continue for an additional 12 months or so, reaching to 115 EJ/yr and then level off and start to decline before 2030, falling to 64 EJ/yr by 2050 (Figure 4.4).

FIGURE 4.4

World oil demand by sector

Units: EJ/yr



Note: Non-petrochemicals includes bitumen, asphalt, and lubricants.
Historical data source: IEA WEB (2024)

As electrification in road transport accelerates, oil use will decline between 2035 and 2050 almost twice as quickly as during the period 2025 to 2035. With EVs dominating new vehicle sales from early 2030, oil's share of the transportation road sector declines to 47% towards the end of our forecast period. Passenger and commercial vehicle oil demand will decline 57% and 25%, respectively, over the next three decades.

Oil use in aviation, shipping, and rail transport (collectively termed 'other transport' in Figure 4.4) will initially grow for a few years. Thereafter, the shift toward biofuel, green ammonia, e-kerosene and other low-carbon fuels will reduce this oil demand by 38% from 29 EJ/yr in 2023 to 18 EJ/yr in 2050. Detailed information and analysis for transport fuels are in Section 1.1.

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 21% In 2050. In absolute terms, oil demand for non-energy use will increase from around 24 EJ/yr today to 25 EJ/yr by 2035, then slowly decline back to 24 EJ/yr by 2050, due mainly to a decrease in plastics production caused by demand-side reduction, substitution measures, and higher rates of recycling (see Section 1.5 for more details).

Manufacturing is the third largest user of oil. Its demand will decline slightly from the current 12 EJ/yr to 10 EJ/yr, and its share in oil demand will rise from 7% to 9% by 2050, reflecting the decline in oil demand in other sectors.

Oil or its products are also used in buildings, power, 'other' sectors, and for producing the oil itself. Nevertheless, these uses are small (less than 10% of total oil demand) and will remain so throughout our forecast period.

> As electrification in road transport accelerates, oil use will decline almost twice as quickly between 2035 and 2050 as during the period 2025 to 2035.

Regional demand

Peak oil demand and production vary significantly by region (Figure 4.5). High-income regions peak early, while low-income regions either peak later or outside our forecast period. Much like the broader energy demand trend, global oil demand is shifting eastward and southward. North America had the highest absolute level of oil demand for many decades, but the region's projected escalation of electrification in road transport over the next few years means Greater China will surpass North America's oil demand after 2026. Our forecast shows that by 2050, the Middle East and North Africa, Greater China, and the Indian Subcontinent will emerge as the top three regions for oil demand. The bottom three will be Sub-Saharan Africa, OECD Pacific, and Europe. Table 4.1 compares forecast growth rates for crude oil demand in each region up to 2050.

Although North America's absolute oil demand will decrease drastically because of EV growth, its demand per capita is projected to remain the highest in the world for the next two decades. By 2050, North East Eurasia will have the highest oil demand per capita followed by the Middle East and North Africa and North America (Figure 4.6). Sub-Saharan Africa will maintain a much lower oil demand per capita than the other regions throughout the forecast period.

TABLE 4.1

Crude oil demand growth rate per region

Year / Region	North America	Latin America	Europe	Sub-Saharan Africa	Middle East and North Africa	North East Eurasia	Greater China	Indian Sub-continent	South East Asia	OECD Pacific
2023 to 2030	-17%	4%	-15%	5%	10%	-11%	-6%	33%	15%	-13%
2030 to 2040	-33%	2%	-34%	36%	1%	-13%	-31%	15%	7%	-32%
2040 to 2050	-42%	-17%	-39%	32%	-12%	-4%	-29%	-8%	-2%	-43%

FIGURE 4.5

Crude oil production and consumption by region

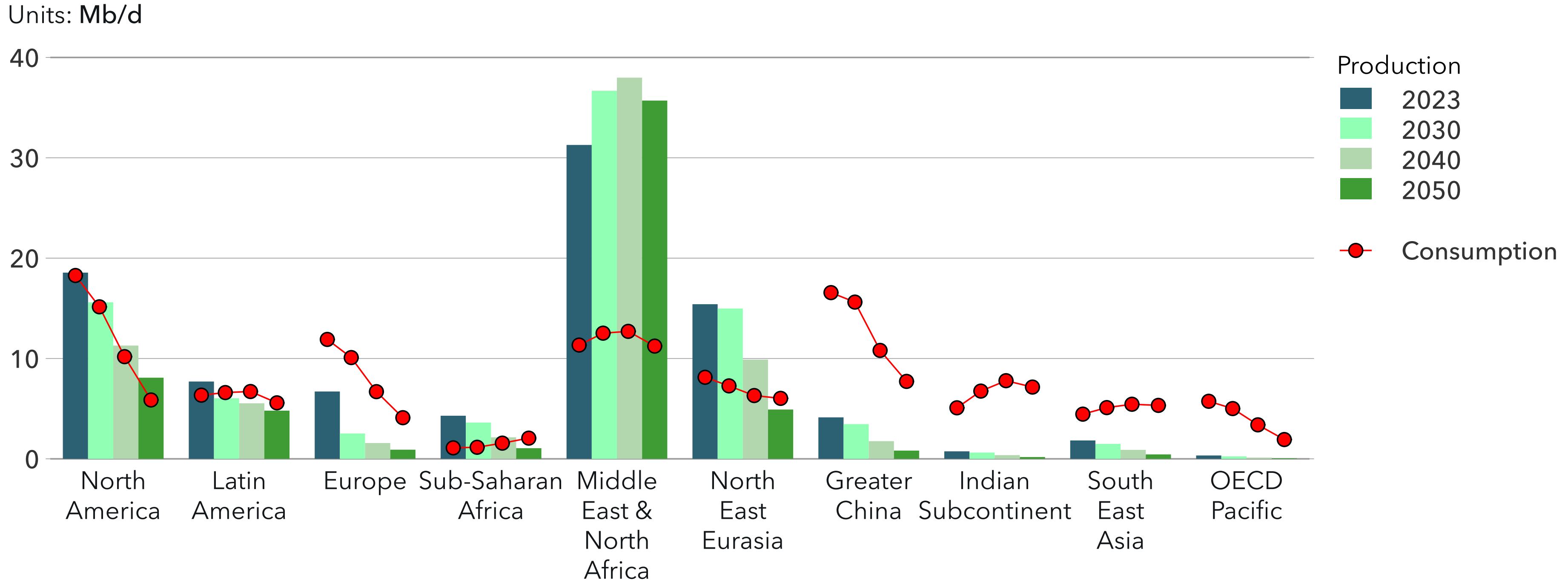
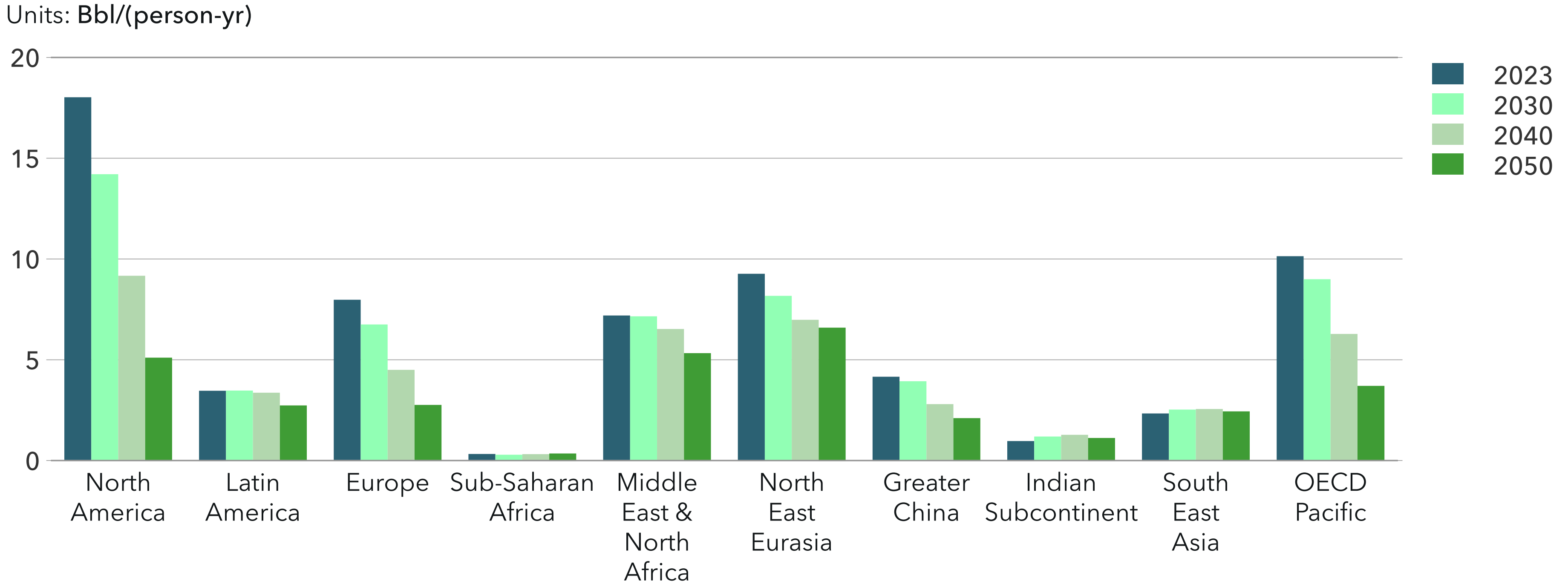


FIGURE 4.6

Crude oil demand per capita by region



Production and trade

The overall oil supply growth in 2023 was approximately 1 Mb/d, a slowdown from the previous year when the growth was significantly higher due to the recovery from the pandemic and OPEC+ adjustments. The increase in production came primarily from non-OPEC+ countries like the US, Brazil, and Guyana, while OPEC+ nations saw a decline in output largely because of the voluntary cuts led by Saudi Arabia and Russia. We expect global oil production to grow modestly, less than 1Mb/d in 2024 and 2025 before it starts declining in 2026.

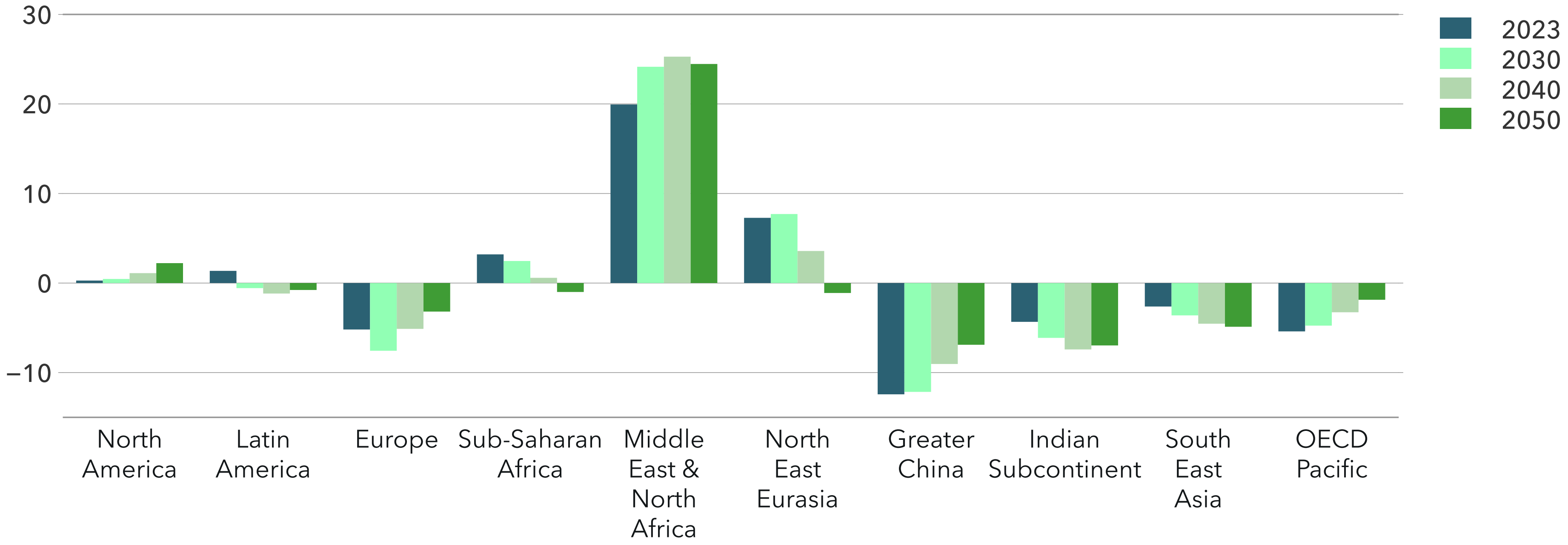
The Middle East and North Africa, North East Eurasia, and North America are net oil exporters and will continue exporting throughout our forecast period (Figure 4.7). Greater China, Europe, the Indian Subcontinent, OECD Pacific, and South East Asia will remain net oil importers, with import volumes projected to decline sharply for Greater China, Europe, and OECD Pacific, while the Indian Subcontinent and South East Asia are expected to see substantial increases in their oil imports. Latin America will be a net oil importer before the end of this decade.

Upstream investments in oil production nearly reached USD 580bn in 2023, an 11% increase from the previous year due to high oil prices and strong financial positions of companies. According to IEF, these investments are projected to rise a further USD 26bn in 2024, surpassing USD 600bn for the first time in a decade (IEF, 2024). 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 nearly double to 63% due to rapid reductions in other regions (Figure 4.5). Production in the Middle East and North Africa will climb from 31 Mb/d in 2023 to 36 Mb/d in 2050. The region has the lowest cost-per-barrel oil production, a critical factor for market share retention as demand reduces and market competition tightens. As production decreases and prices increase, we expect importer regions to focus on energy security and further boost renewable energy at regional and local levels. Consequently, oil's significance in the geopolitical landscape is likely to wane in the coming decades.

FIGURE 4.7

Oil net export by region

Units: Mb/d



The global oil trade landscape is still evolving with new trade routes and market dynamics. These changes are driven by geopolitical events, economic conditions, and a growing focus on sustainability. Ongoing geopolitical issues, such as tensions in the Middle East and the Russia-Ukraine conflict, create uncertainties in the oil market. For example, Russian oil, which used to be a major supplier to Europe, has found new markets primarily in Asia, with China and India becoming prominent buyers of Russian crude at discounted prices.

Our model separates offshore, onshore conventional, and onshore unconventional oil production. As unconventional capacity has a shorter average lifetime than conventional, onshore and offshore regional distributions of capacity additions are not directly comparable. Globally, the distribution remains relatively stable over the forecast period.

We stress that uncertainty over where oil will come from is high. In our ETO model, produced oil is assumed to be consumed by equal levels of oil demand and regions will not develop their oil resources if cheaper oil can be supplied by other regions. Although limited storage means that global oil production will always equal demand over time, regional distribution might not follow the same disciplined pattern assumed in our model. The reduction in 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.

Scope 3 emissions

Scope 3 emissions include all indirect emissions that occur in the value chain of a reporting company. This excludes direct emissions from owned or controlled sources (Scope 1) and indirect emissions from the generation of purchased electricity (Scope 2), such as electrification of platforms to reduce emissions during production. Unlike Scope 1 and 2, reporting Scope 3 emissions is not mandatory as of 2024. However, in some regions, such as Europe, companies need to begin reporting in 2025 under the *Corporate Sustainability Reporting Directive* (CSRD). In the US, California mandates Scope 3 reporting for any company operating in the state with more than USD 1bn in annual revenue. Other proposed regulations and reporting standards, such as the *International Sustainability Standards Board* (ISSB), are being adopted by countries such as the UK, Australia, and Canada. Scope 3 reporting has been removed from the US SEC climate-related disclosure final rules (Aligned Incentives, 2024).

The complexity and global span of supply chains make it challenging to measure Scope 3 emissions comprehensively. Additionally, the lack of standardized methods and frameworks for calculating and reporting these emissions, as well as the difficulty in attributing emissions to specific activities, further complicate the process. Nevertheless, Scope 3 emissions represent most of oil and gas's carbon footprint and can often account for up to 90% of total emissions. This is due primarily to the use of sold products: the combustion of fossil fuels by end-users (Scope 3, category 8). To mitigate this, the industry is implementing carbon capture and storage (CCS) and direct air capture (DAC) technologies to remove emissions occurring at end-use. Understandably, there is debate about how far oil and gas producers should go in addressing their Scope 3 emissions. Reporting these emissions can be viewed, at the very least, as placing data on a common table that can be used for decision making. However, there is strong opposition within the industry towards the setting of Scope 3 targets. Oil and gas producers argue that it is more sensible to incentivize end-users to look for ways to reduce their Scope 1 and 2 emissions by enhancing energy efficiency, switching to lower-carbon fuel, or switching completely to renewable energy sources.

4.3 NATURAL GAS

Natural gas surpassed coal in the early 2000s and is projected to overtake oil by the mid-2030s to become the world's leading energy source. The transition to gas is propelled primarily by local environment and climate considerations that favour gas for its lower carbon intensity and higher efficiency. Extensive pipeline networks and liquefied natural gas (LNG) infrastructure allowing easy distribution supports this shift.

Global gas demand in 2023 grew only about 0.5% over the previous year to 4,920 billion m^3. This was largely due to a tight supply as the increase in global LNG production (up 13 billion m^3) was not enough to offset the continued decline in Russian piped gas deliveries to Europe (down 38 billion m^3). However, preliminary data shows that global gas demand will likely grow by 2% in 2024. We project that this demand will slightly increase, reaching 5,200 billion m^3 around 2026 and then plateau for three to four years before gradually declining to 4,420 billion m^3 by 2050.

Over the last decade, natural gas has consistently accounted for around 25% of the global primary energy supply. We forecast that it will maintain this share until 2030 before declining to 22% in 2050. Future natural gas demand will vary by region, typically increasing in low- and middle-income regions and reducing in OECD regions. 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.

Sectoral demand

Natural gas demand has grown over the past two decades, but the distribution between sectors has remained relatively consistent (Figure 4.8). Total natural gas demand in 2023 was 172 EJ. This will increase to 182 EJ in 2026 and stay at that level for five years before declining to 158 EJ in 2050.

– 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 2030 before reducing to 22% (35 EJ) by the end of our forecast period due to the expansion of renewable energy sources.

– Demand for gas from the buildings sector will increase from 35 EJ in 2023 to 40 EJ in 2050 as it replaces coal and biomass in cooking and heating.

– Demand for gas in manufacturing is projected to grow from 29 EJ today to 34 EJ by 2050, as it replaces coal.

– Starting from a relatively low baseline of 8 EJ, gas demand in the transport sector will rise to 11 EJ by 2035 but will then decline to 9 EJ by 2050 due to being displaced by hydrogen derivatives such as ammonia and e-fuels in shipping.

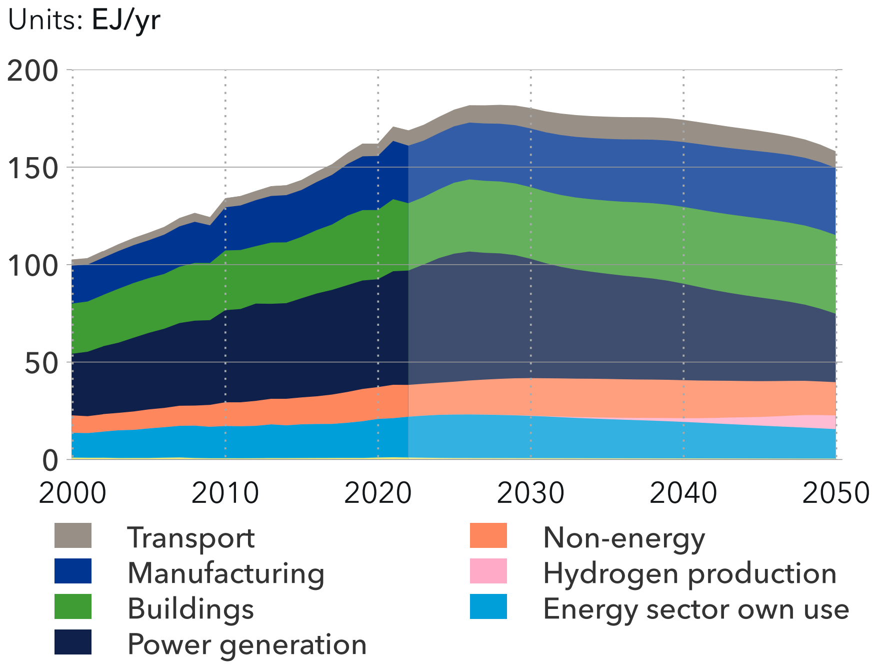
– The share of non-energy applications (largely petrochemicals) in gas demand will remain stable at around 10%, as the demand for products using gas as a feedstock holds steady and hydrogen use increases.

– We expect own use (demand from the oil and gas and energy industries during production and distribution) currently at 22 EJ, to remain steady until 2030 before decreasing to 15 EJ by 2050. 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 production to increase from negligible levels in 2022 to 11 EJ by 2050.

FIGURE 4.8

World natural gas demand by sector



Includes natural gas liquids and biomethane. Historical data source: IEA WEB (2024)

Regional demand

In 2023, the natural gas demand growth varied across regions. Demand grew in China (7%), India (5%), North America (1%), North East Eurasia (1%), and the Middle East and North Africa (2%). However, these increases were partially offset by declines in other regions like Europe (-7%) and Latin America (-5%). Europe's power sector accounted for 75% of its decrease in demand, driven by lower electricity consumption and the continued expansion of renewables.

In Europe and OECD Pacific, gas demand will keep declining to about 40% of 2023 values by 2050 (Figure 4.9). In Greater China, it will grow 40% by 2040, plateau until 2045, and then decline to 680 billion m^3.

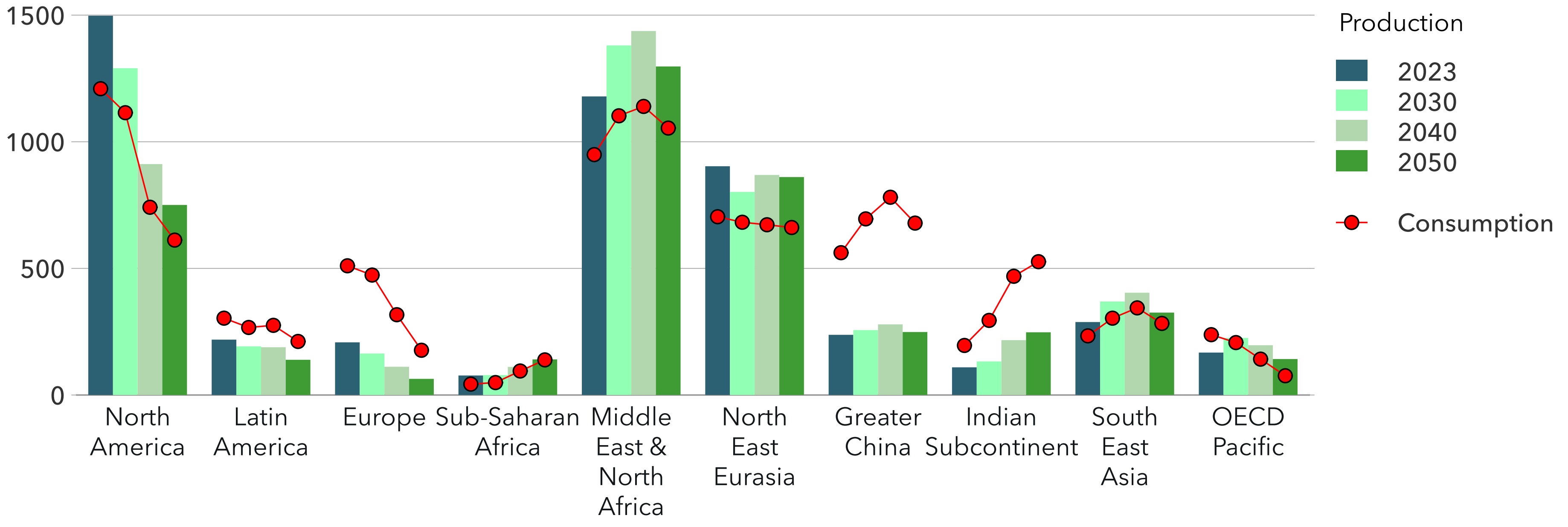
Gas demand in the Indian Subcontinent and Sub-Saharan Africa will triple by 2050. The rise in demand in Greater China and the Indian Subcontinent is driven by strong policy support for natural gas consumption in the short term and the shift from coal to gas to reduce local pollution.

> We forecast that gas will be 25% of primary energy until 2030 before declining to 22% in 2050.

FIGURE 4.9

Natural gas production and consumption by region

Units: Bn m^3/yr



Production and trade

In the coming years, we expect global natural gas production to increase by 1% to 2%, mirroring demand trends, before leveling off until the 2030s. Afterward, production is projected to gradually decline to 85% of its current level by the end of our forecast period. By 2050, Middle East and North Africa gas production will increase by 10% and its share also increases by 7% to 31% (Figure 4.9). At the same time, production in North America and Europe will be reduced to half and one-third, respectively, reflecting the decrease in domestic demand. We project North East Eurasia's gas production and its global share to be slightly lower than current values. Over the course of our Outlook, natural gas net export and import will continue to vary by region (Figure 4.10).

- Middle East and North Africa, North America, and North East Eurasia were the top natural gas exporting regions in 2023, with exports of 534, 388, and 215 billion m^3, respectively. We expect North East Eurasia's export volume to double by the 2040s, despite a near-zero export volume to Europe in 2021, as China and India increase their imports. Initially, these exports will be routed through LNG, followed by the development of new pipelines. Conversely, we project North America's export volume to gradually decrease by 25% by 2050.
- OECD Pacific currently leads in interregional trade, with Australia as the world's second-largest LNG exporter and Japan and South Korea as major importers. However, from 2024 onward, increased production in Australia combined with decreased demand in Japan and South Korea will lead to a supply surplus, shifting the region from a net importer to a net exporter.
- Europe has been the largest importer region in recent decades, importing 453 billion m^3 in 2023 – an 11% decrease from 2022. We expect this trend to continue, with imports projected to fall to one-third of current levels by 2050.
- Greater China and the Indian Subcontinent both face high demand and limited domestic natural gas resources. In Greater China, gas imports will rise until 2040, after which we expect them to decline through 2050 as domestic consumption decreases. We also expect the Indian Subcontinent to significantly increase its LNG imports to meet a nearly threefold surge in demand. This will necessitate substantial growth in LNG regasification capacity in the region.

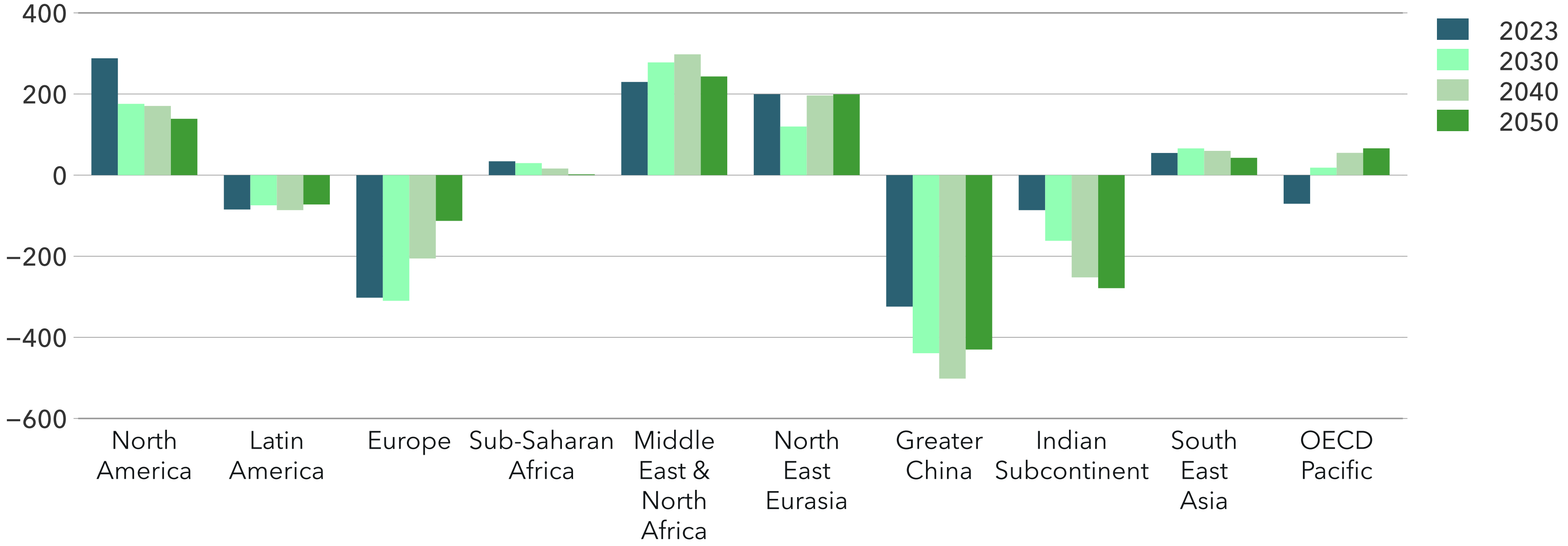
The cost of delivering gas from producer regions to consumer regions influences trade. Gas transport is expensive and accounts for a significant proportion of the cost of delivered energy. Piping gas is cheaper than shipping it for shorter distances, but we still expect LNG to increase its share because it is more efficient for long-distance transport. In fact, both pipeline and LNG transport will increase even when global gas decreases because of a shift in demand patterns to regions with little pipeline import and a heightened focus on energy security and supply diversity. However, regional capacity for regasification and liquefaction vary by region, limiting the potential for LNG. The Middle East and North Africa region has the largest installed liquefaction capacity today and will increase by 26% between 2040 and 2050. North America – being distant from its natural gas export customers – will increase its liquefaction capacity by 37% by 2030. LNG liquefaction capacity stays the same in other regions up to mid-century. Regasification capacity will increase by 50% in the importer regions of Greater China and the Indian Subcontinent between 2023 and 2050.

> We expect the Indian Subcontinent to significantly increase its LNG imports to meet a near-threefold surge in demand. This will require a substantial growth in regasification capacity in the region.

FIGURE 4.10

Net natural gas export by region

Units: Bn m^3/yr



Energy sector 'own use' of energy

Energy sector own use is the intermediary input in the production process that includes fuel use in operations such as extraction, processing, and distribution. It is distinct from the final energy consumption by end users. Natural gas and bioenergy are the primary sources of energy for the energy sector's own use, but electricity is quickly catching up.

Looking towards 2050, we predict the total energy sector's own use to decrease by about 16% from 2023 levels. This reflects significant efficiency improvements and shifts towards cleaner energy sources across various regions and sectors.

- Power stations remain a major consumer of energy within the sector, accounting for about 27% of the total energy sector's own use by 2050.
- The energy used in oil refineries for the operation of equipment, heating, and lighting has historically had the largest portion of energy sector's own use. With reduced oil demand, the energy consumption of the refineries will decline accordingly.
- We project oil and gas extraction to decline in energy use, particularly in Europe and North America, due to the transition toward electric vehicles and alternative fuels. However, extraction remains significant in regions with abundant oil and gas resources, such as the Middle East and North Africa. In these areas, efforts are focused on improving efficiency and reducing emissions through technological innovation and electrification.

We forecast energy consumed for coal mining and processing to see a global decline as cleaner energy sources become more prominent, constituting only 1% of total energy sector's own use in 2050.

We expect carbon capture and storage (CCS) technologies to grow, especially in regions like China. While CCS energy use starts from a relatively low base, we expect it to increase substantially because regions dependent on fossil fuels see it as crucial for reducing emissions. We anticipate Direct air capture (DAC) to become increasingly important in technologically advanced regions such as North America and Europe. We project that the energy used for DAC rise as the technology becomes more viable and plays a critical role in achieving negative emissions, particularly after 2040.

The role of electricity within the energy sector's own use is expanding as power stations, DAC, and other new technologies increasingly rely on it for operations. This expansion is supported by investments in grid infrastructure and energy storage technologies, facilitating the integration of a higher share of renewable energy into the electricity mix. The sector's own use of electricity is also expected to rise due to DAC systems, which we project will become more widespread, particularly in regions investing heavily in carbon reduction technologies. We expect DAC to increasingly use electricity instead of natural gas due to advancements in capture technologies that reduce heat requirements and enhance efficiency. Electrically powered systems, such as those using solid sorbents, require less heat compared with traditional gas-based systems that rely on liquid solvents, making electricity a more suitable and cleaner option.

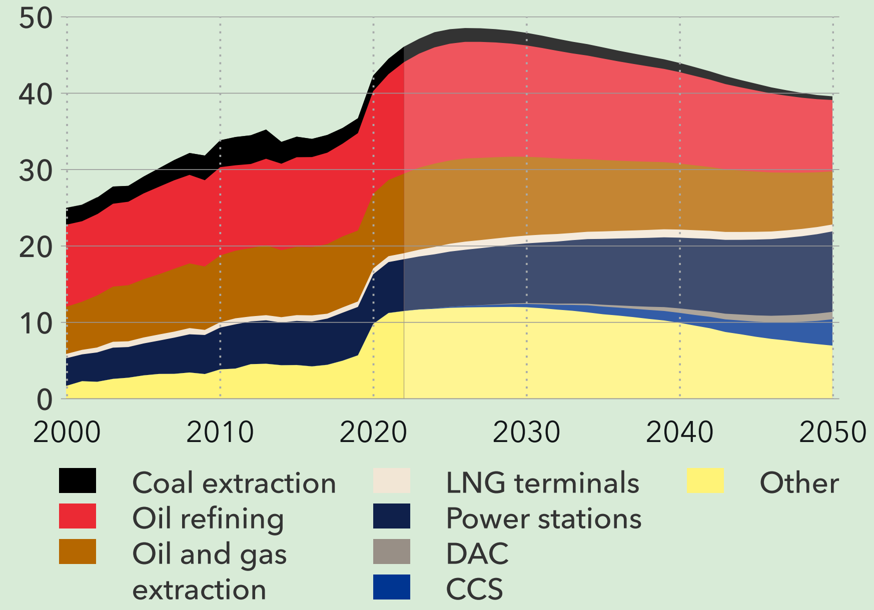
Natural gas remains a vital component of the energy sector's own use, particularly in regions like the Middle East and North Africa where it is abundant. It is used extensively in oil and gas extraction, refining. However, as the energy sector moves towards decarbonization, the energy sectors that consume natural gas for their operations start to scale down.

Bioenergy is another key energy carrier in the energy sector's own use, primarily reported in regions such as Sub-Saharan Africa and Latin America, which includes net energy consumption of charcoal production plants and other unspecified uses.

FIGURE 4.11

Energy sector's own energy use by source

Units: EJ/yr



Historical data source: IEA WEB (2024)

4.4 SUMMARIZING ENERGY SUPPLY

In this section, we summarize the primary supply of energy from all energy sources, including fossil fuels. DNV uses the primary energy content method in its calculations.

Global primary energy supply represents all produced energy and includes the energy sector's own use. We predict that the primary energy supply will remain nearly flat from 2030 to 2045, with a slight decline onwards despite the continued growth of the global population and economy (Figure 4.12 and Table 4.2). A major reason for this is that conversion and transport losses – for example, heat losses in a power plant converting coal to electricity or electrical power lost as friction in grids – will reduce considerably as the share of non-fossil energy increases (see Chapter 1.5 for more detail). These conversion losses alone currently exceed 100 EJ per year. Global primary energy consumption is therefore considerably higher than final energy consumption. In 2023, primary energy supply was 634 EJ, while final energy demand was 457 EJ. Primary energy supply will grow slowly to reach its maximum in 2038 at 673 EJ/yr, 6% higher than today, then reduce about 3% to 655 EJ in 2050.

The primary energy supply mix will change significantly through to 2050 with fossil fuel's share falling from 80% today to 50% in mid-century. In historical terms, this reduction of more than one percentage point per year for fossil fuels is comparatively fast. This change accelerates throughout our forecast period, suggesting that the trend will continue well beyond 2050.

The decline is quickest for coal, falling from 25% to 9% over the next 27 years. This is followed by a decrease in oil's share, which will drop from 30% to 19% over the same period, while natural gas's share will decline slightly from 25% to 22%.

The share taken by nuclear energy will increase slowly over the forecast period, ending at 6% in 2050. In contrast, renewables' share will triple from 15% today to 44% by the end of the forecast period. Within renewables, the large increase will be driven by solar and wind, which will see 14-fold and 9-fold increases in primary energy supply towards 2050, respectively. Solar will reach 18% and wind 10% of the global primary energy mix in 2050, with further growth expected beyond mid-century. Bioenergy and hydropower will also grow, in both relative and absolute terms.

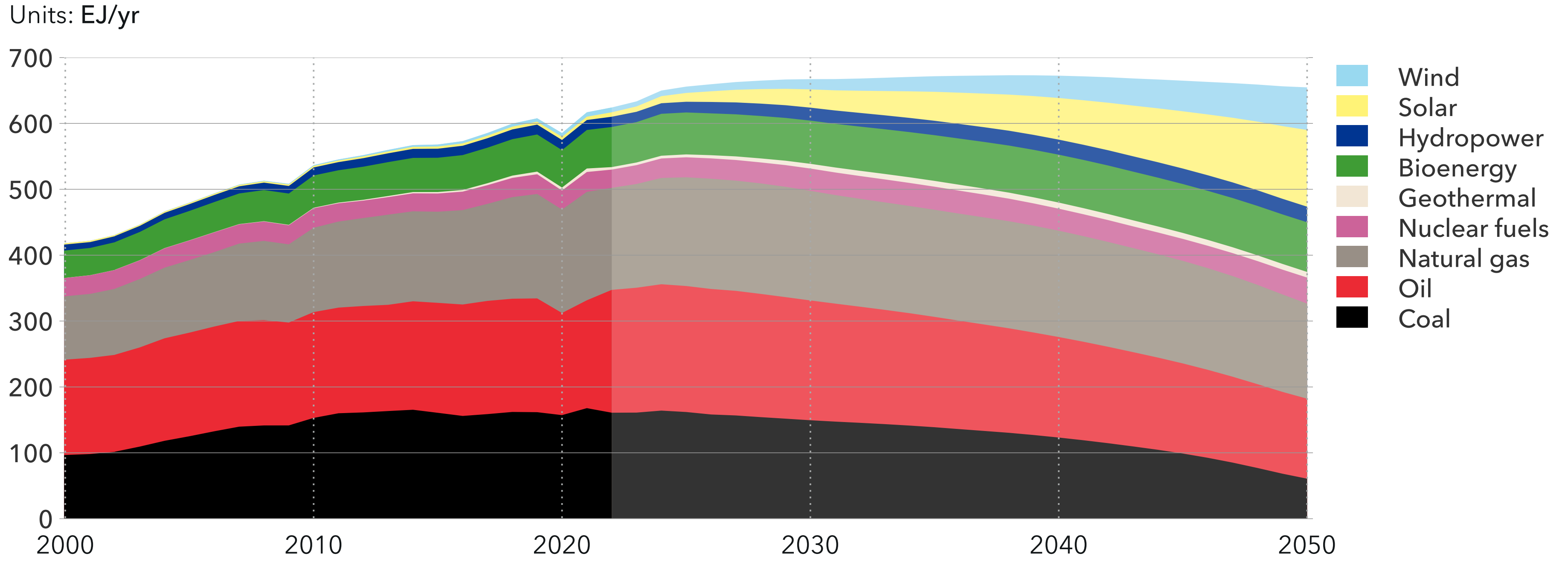
TABLE 4.2

World primary energy by source (EJ/yr)

Source	2023	2030	2040	2050
Wind	8	16	34	65
Solar	8	28	63	117
Hydropower	16	20	23	24
Bioenergy	61	65	73	75
Geothermal	4	7	9	9
Nuclear	29	34	34	40
Natural gas	157	166	162	144
Oil	189	182	152	121
Coal	161	150	123	60
Total	**634**	**668**	**673**	**655**

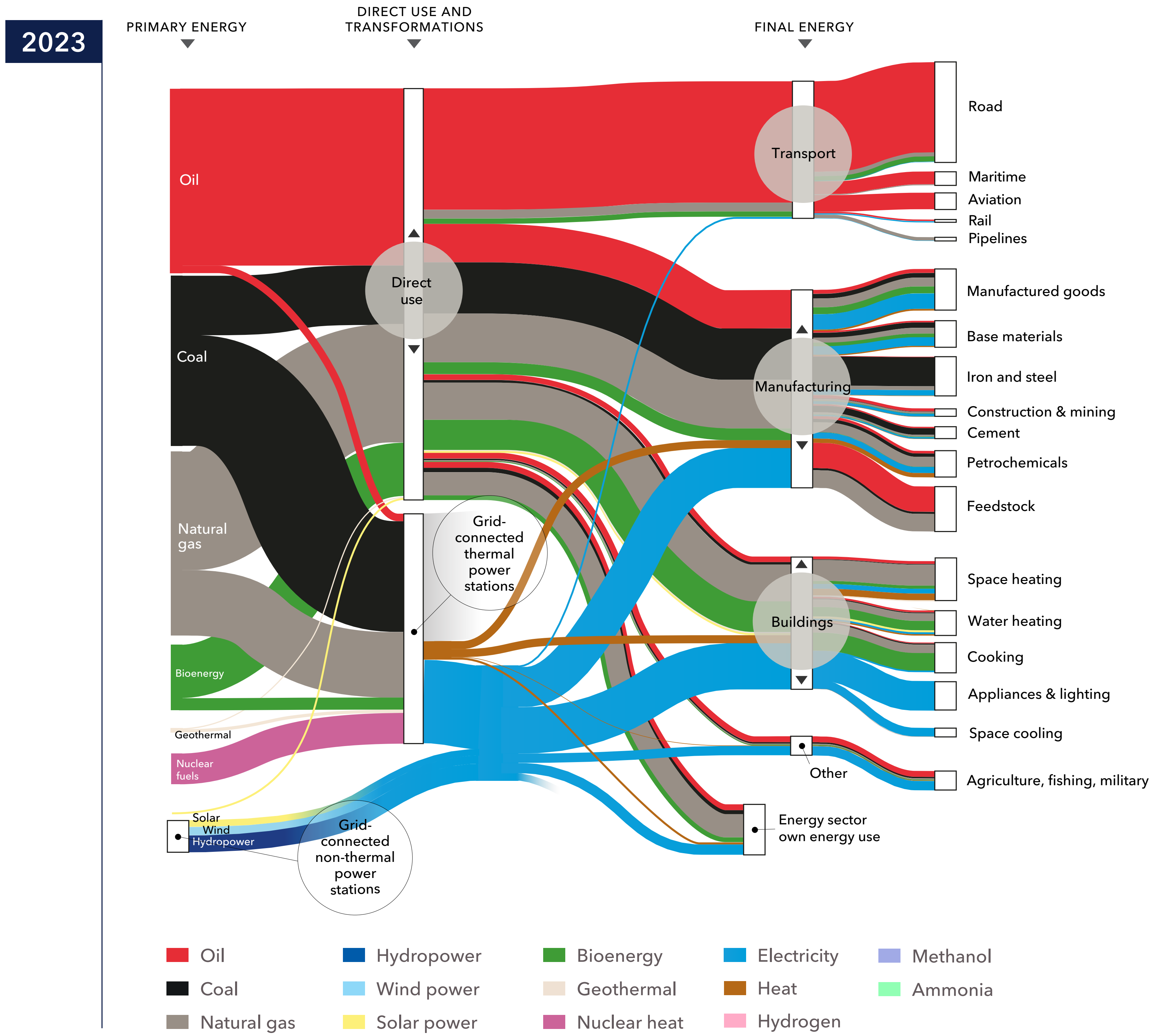
FIGURE 4.12

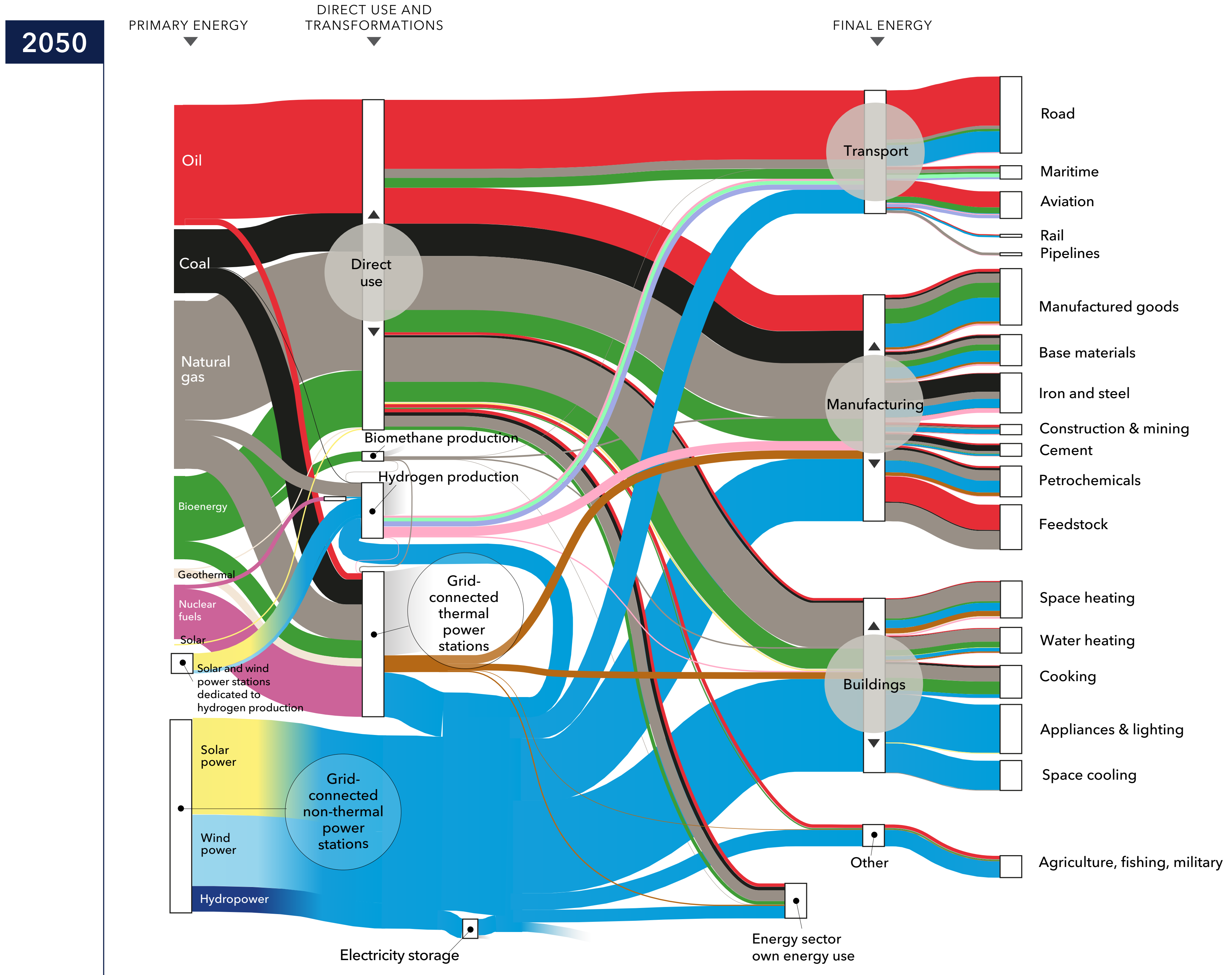
World primary energy supply by source

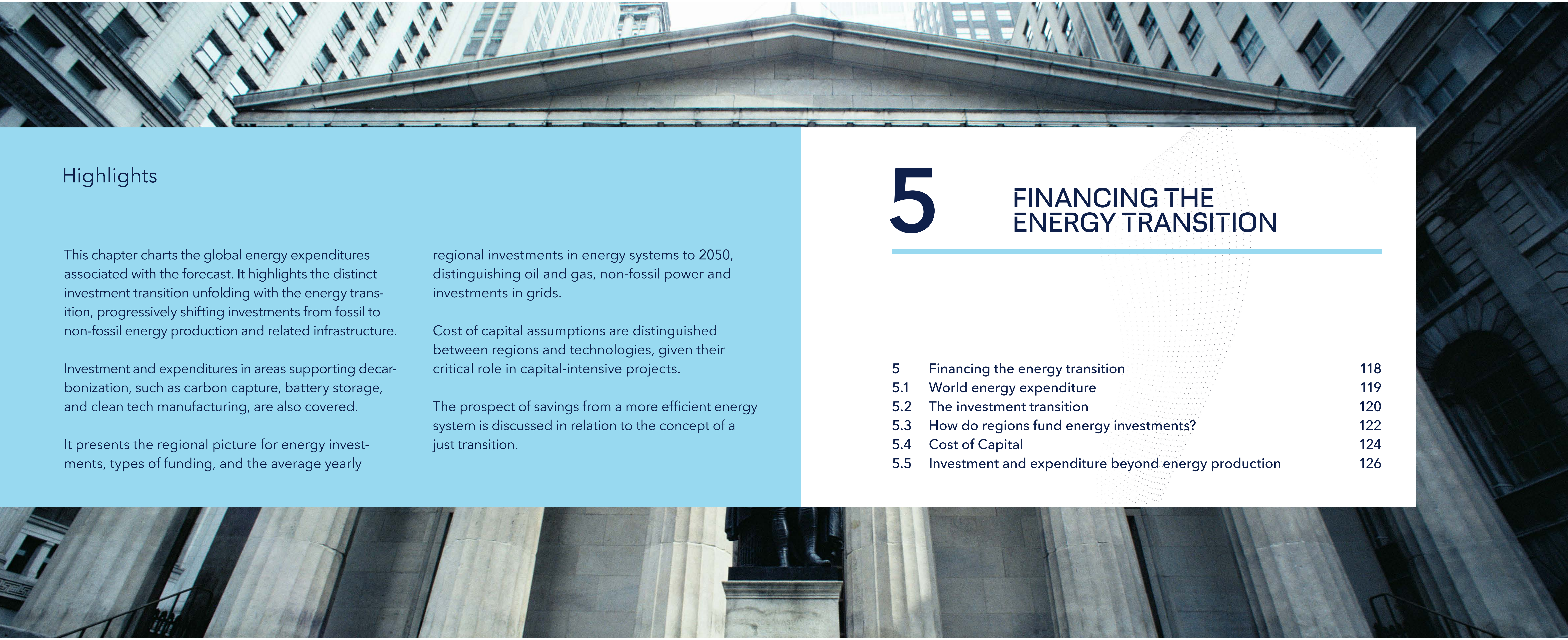


Historical data source: IEA WEB (2024)

COMPARISON OF ENERGY FLOWS







5

FINANCING THE ENERGY TRANSITION

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Highlights

This chapter charts the global energy expenditures associated with the forecast. It highlights the distinct investment transition unfolding with the energy transition, progressively shifting investments from fossil to non-fossil energy production and related infrastructure.

Investment and expenditures in areas supporting decarbonization, such as carbon capture, battery storage, and clean tech manufacturing, are also covered.

It presents the regional picture for energy investments, types of funding, and the average yearly regional investments in energy systems to 2050, distinguishing oil and gas, non-fossil power and investments in grids.

Cost of capital assumptions are distinguished between regions and technologies, given their critical role in capital-intensive projects.

The prospect of savings from a more efficient energy system is discussed in relation to the concept of a just transition.

5 FINANCING THE ENERGY TRANSITION

Large, upfront investments will be needed for the rollout of renewables, battery storage, and the grid. This requires new financing mechanisms and investors, and different strategies in the different world regions. At the same time, as demand for fossil fuel starts to fall away, so will enormous operating costs – relative to the low cost of operating renewable technologies. Moreover, electrification accelerates efficiency gains such that the overall result of the energy transition will be substantial economic gains at a global level.

DNV has emphasized this message consistently over the years in our annual *Energy Transition Outlooks* that the energy transition involves a substantial green reward and will pay dividends to investors and society for generations to come. The magnitude of these savings suggests that a faster transition and, indeed, a just transition could be within reach, However, this will require a substantial change in policy from the 'most likely' future we forecast.


Photo, Michael Bobbin

5.1 WORLD ENERGY EXPENDITURE

Energy expenditures are the upstream costs related to the production of energy and its transport to the user, including operational expenditure (OPEX) and capital expenditure (CAPEX). Total world energy expenditure was USD 6.1trn in 2023, of which three-quarters went to fossil energy. We project that while global GDP will nearly double by 2050, world energy expenditure will only increase by 5% to USD 6.5trn. In our view, therefore, those who argue that the energy transition involves significant amounts of capital expenditure without improving the efficiency of capital and labour are very much mistaken.

The drivers behind this surprising expenditure stability are electrification and the general increase in energy efficiency (much of which is related to electrification), which are decoupling economic growth and final energy demand. As a result, while unit carbon intensity will be halved, unit expenditure on final energy, the energy directly delivered to end users (as oil, gas, or electricity) at the point of its first use, will stay stable around USD 40 to 50/MWh.

The unit cost will even decrease if considering 'useful energy', the energy which is converted into energy services (heat, transport, etc.) with associated losses (waste heat). As we show in Section 1.5, one MWh of final energy delivers 0.64 MWh of useful energy today. In 2050, one MWh of final energy delivers 0.94 MWh of useful energy, which equates to an average efficiency increase of 48%. Expenditures are not market prices paid by the consumer, which include margins, taxes, and/or subsidies. However, if one holds the unit price of final energy stable assume that margins, taxes, and subsidies. do not change greatly, our forecast shows that as end use electrifies and consumers take advantage of the associated improvements in energy efficiencies. The result is that customers will pay less for the same output and energy bills will decrease in most regions (DNV, 2023). Besides limiting energy expenditures, the transition provides additional economic benefits:

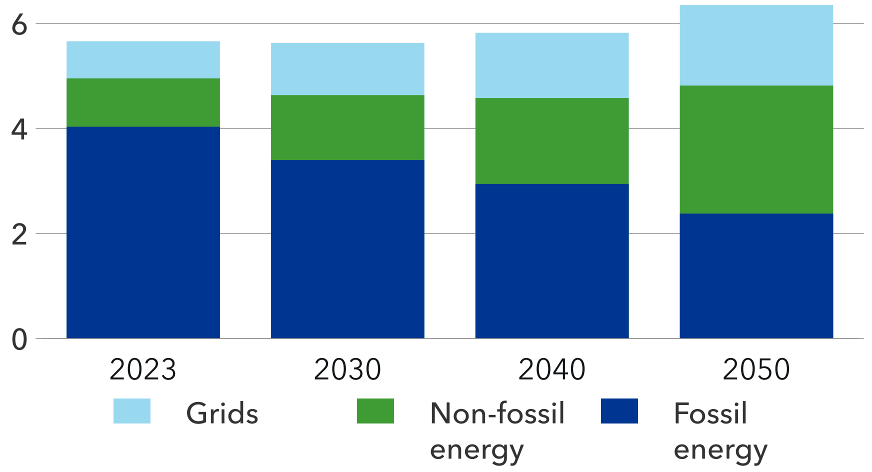
- **Job creation:** investments in clean technologies are projected to create more jobs (in construction, manufacturing, and maintenance) and, as a result, provide more local economic benefit than fossil-fuel investments (WRI, 2021).
- **Economic growth:** investments in renewable energy can stimulate economic growth by increasing demand and output in related industries (UNDP, 2021).
- **Additional external cost savings:** these arise from slowing climate change and avoiding its impacts, and through the considerable financial benefits of cleaner air (OECD, 2016).
- **Better resilience:** diversifying energy sources reduces dependence on imported fuels, enhancing national energy security and stability. Renewable energy systems can also be more resilient to extreme weather events and other disruptions compared with traditional energy systems (UNECE, 2022).

However, the transition poses some challenges, and inequalities are likely to persist. As described later in this chapter, a 'just transition' is within reach, but will require active political effort.

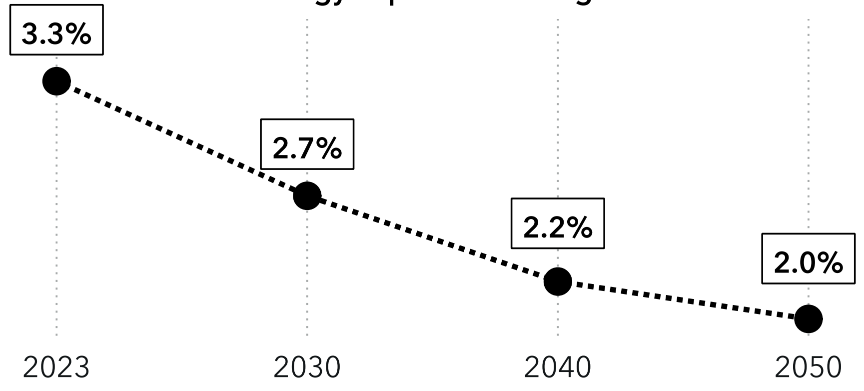
FIGURE 5.1

World energy markets indicators

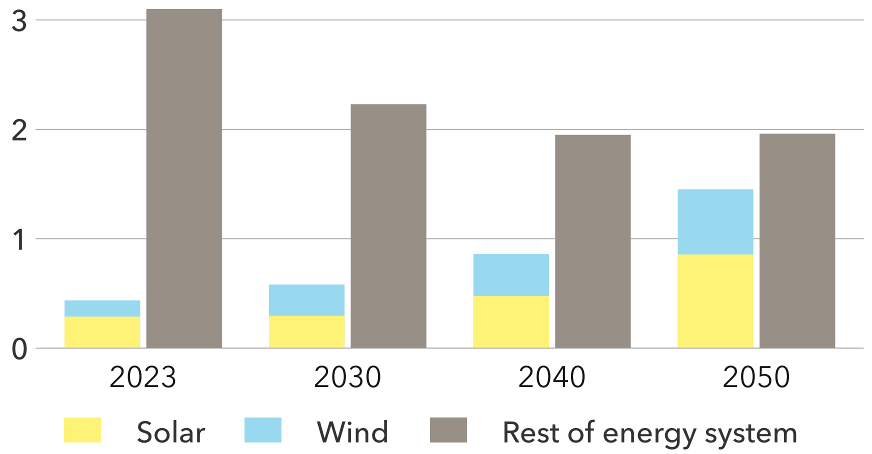
Global energy expenditures (trillion USD/yr)



Share of energy expenditures in global GDP



Breakdown of investments (trillion USD/yr)



Monetary values stated in real 2023 USD

5.2 THE INVESTMENT TRANSITION

The forecast energy system comes with a gradual transfer of expenditures from fossil to non-fossil sources and grids, with a resulting shift from OPEX to CAPEX in a more electrified energy system. Regional energy investments will also be affected, with more energy being produced and consumed locally.

This means that the energy transition is an investment transition characterized by changes in capital flows, risk models, and the financial landscape.

Changing capital flows

Capital structures for financing renewable investments differ from fossil energy investments. Last year, we saw investment in solar and wind, once niche sectors driven by policy mechanisms, reach a record combined USD 440bn globally. Capital flows will continue to find their way to more energy transition asset types, and therefore increasingly finance new equipment and installation rather than maintenance and operations.

Changing risk models

Capital for energy investments is typically a mix of debt and equity. Debt involves funding that requires interest payments, while equity generally refers to the capital provided by the project owner or developer. Investment can vary widely in its funding structure, ranging from fully debt-financed to fully equity-financed projects. Typically, we see higher shares of debt financing in the power generation sector, especially in developed markets, and lower shares of debt in riskier markets. With the electrification of society, there will be increased exposure to electricity markets and reduced exposure to oil and gas markets. New financiers should fully understand the varied dynamics and risks of electricity markets before entering this growing investment opportunity space. This requires financiers to learn, change, and build new risk models.

> Depth of access to finance is an under-communicated strength of scalable renewable technology.

Changing financial landscape

Funding approaches vary widely by region. There is no universal method, and large regional differences remain regarding who provides the financing and how it is structured. The funding strategy depends on the specific type of energy investment and the region's economic capacity and infrastructure. We see that fossil energy is solely financed by governments and corporates, while renewables, especially scalable technologies like solar and batteries, are also increasingly financed by households. This change to the financial landscape impacts access to capital and Cost of Capital (CoC). Depth of access to finance is an under-communicated strength of scalable renewable technology.

The case for solar

In contrast to fossil-fuel projects, there has been rapid and consistent growth in solar PV investment across the world over recent years (DNV, 2023). Last year's record investment in solar PV generation (USD 290bn) even exceeded our expectations. Investment in new solar PV installations now exceeds investment in all other new generation technologies combined. This drives rapid change: in 2015, we saw an investment ratio of 2:1 for money spent in clean power vs. fossil power, and this will be 10:1 in 2024 (IEA, 2024a). New generation in the power sector is dominated by clean power, with solar PV in the driver's seat.

Solar's scalability and wide allows it to attract all kinds of investors, from households to governments and corporates. Household financing differs in the sense that it is available, but in low quantities per household, with poor risk management. Sub optimal financing structures, lagging regulations to protect consumers and high failure rates for residential systems all drive up CoC for households compared with governments and large corporations. Whether a project calls for one small panel at a home or 2.3 GW of panels in the Thar desert in India, the basic product is the same. This makes solar PV a unique technology with unequalled scalability potential. The upfront investment cost can be sized 1:1 to the available capital. We expect that households will take a larger share of the funding: each installed solar cell drives an investment transition, while the small size of a single project lowers financing hurdles. This exemplifies a key takeaway: we expect that funding sources will change with the applied technology, and that access to capital for solar PV investments is better than for other technologies because it has lower upfront costs and a larger share of investment made by households.

Solar investment is less susceptible to political instability than other technologies. This improves access to capital in regions like Sub-Saharan Africa where the likelihood of political instability historically meant that financiers lacked trust to allocate capital. For large-scale solar PV, the investment case in Sub-Saharan Africa remains challenging due to investors demanding high interest rates to cover country risk, currency risk, and contractual reliance on local governments. Hence, it is at the level of smaller-scale installations where financing costs, due to increased access to finance, can make a difference.

This small-scale momentum is not similarly available to emerging clean technologies like green hydrogen or (floating) offshore wind, technologies known for very high upfront capital costs per installation. We expect that funding for these technologies will come from similar sources to those for onshore wind, oil and gas, and coal investments – in other words, from governments and corporates.

An uneasy transition away from fossil fuels

DNV forecasts that investment in non-fossil power generation will increase from USD 570bn in 2023 to around USD 900bn per year in 2030 then almost double to USD 1,700bn annually in 2050, representing a quarter of energy expenditures by that year. In the meantime, investment in fossil energy will progressively decrease; though even in the 2040s, upstream production of oil and gas will still represent a large share of energy investment (Figure 5.2).

This indicates that the investment transition is not clearly divided between unabated, emission-intensive fossil energy and clean new energy generation. It is a complicated risk picture influenced by global energy transition drivers, geopolitical uncertainty, regional economic development, and local priorities and project specifics. We observe, for instance, a clear market driven movement away from new coal-fired generation, but this will happen at varying rates and by different means.

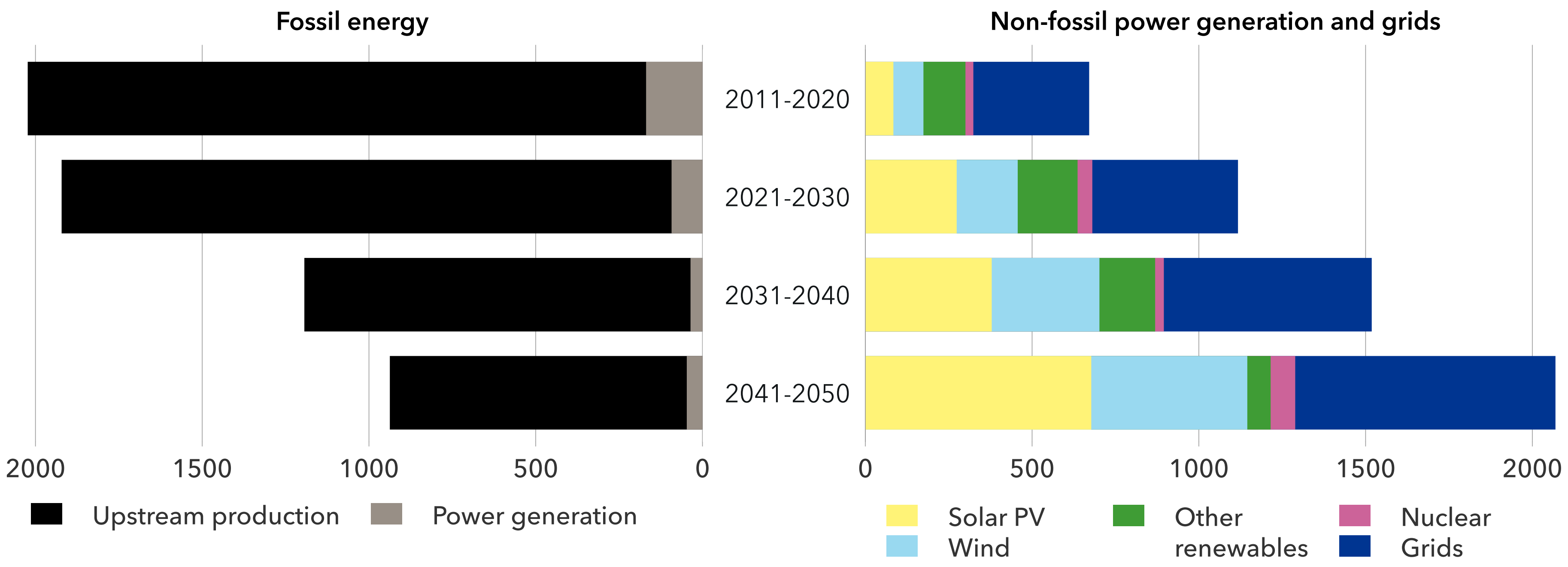
Multilateral finance institutions increasingly prioritize financing renewable energy projects (REN21, 2024). Still, between 2019 and 2022, just under 25% of all development financing was dedicated to fossil fuels (IEA, 2024a). As an example, the African Development Bank (AfDB) and the World Bank provided most of the fossil-fuel finance in Sub-Saharan Africa between 2016 and 2021 (Climate Analytics, 2022), mainly for new fossil gas-fired generation. The AfDB can finance new coal-fired power plants, and while the World Bank's investment standards preclude funding coal plants, it can finance upstream gas if urgently needed for energy security. As a result of these institutions' internal policies guiding investment decisions, capital for the fossil industry will become tighter and more expensive, but the speed of reallocation will differ by region, depending on the energy situation and economic development.

> The investment transition is not clearly divided between unabated, emission-intensive fossil energy and clean new energy generation.

FIGURE 5.2

Average yearly investments in the energy system

Units: USD billion/yr



5.3 HOW DO REGIONS FUND ENERGY INVESTMENTS?

Financial strategies differ significantly between regions, with variations depending on the specific type of energy investment and the region's economic capacity and infrastructure. These differences have a huge impact on the uptake of the different technologies that we forecast.

High-income transition leaders

High-income regions like Europe and North America see most of the funding coming from commercial sources. Their debt and equity markets are fully developed, and risk-mitigation products are available to support financing projects and companies. This means a typical energy investment in these regions is funded with equity from private enterprises, governments in the form of tax credits, or households together with debt from commercial banks and financial institutions (IEA, 2024b). The funding terms – the required return on equity, return on debt, and the leverage – are a direct reflection of risk perception. Voluntary internal financing policies, as well as alliances like the UN's *Net-Zero Banking Alliance*, effectively steer access to capital away from fossil power towards renewables because new energy investments are dependent on private capital.

Regions with large fossil resources

Regions with large oil and gas production, like North East Eurasia and the Middle East and North Africa, see less dependence on bank financing. National oil companies like Rosneft and Saudi Aramco reported record profits in recent years, and new energy investments are largely financed by cashflow from operating activities, with a smaller role for external funding sources (Saudi Aramco, 2023). Oil and gas prices therefore drive access to capital for new fossil energy investments from and within these regions. For coal, we see that European banks that used to finance working capital needs for coal trade are being replaced by banks from coal-producing countries such as Australia, Indonesia, and South Africa.

Regions with stronger state control

Regions where state-owned firms dominate the energy sector, like the Indian Subcontinent and Greater China, unsurprisingly see increasing dependence on public financing. We expect that these regions will also be hot spots for new coal-fired power. Most coal plants in China are state-owned, with state-owned entities providing the bulk of the equity, and state-owned banks incentivized to provide debt financing at supportive terms. New energy investments are therefore directly controlled by the government, and policy changes will rapidly reflect financing structures and terms. Once central policy diverges from economic growth towards reducing air pollution and GHG emissions, financing flows will rapidly dry up. We expect easy access to capital for new coal-fired generation through 2030, followed by a step change in access thereafter. Our assumptions reflect this as increased CoC.

Another consequence of greater dependence on public finance is that it does matter where government cashflows come from. In India for example, the motivation for building out solar PV is not primarily decarbonization, but energy security and India's public finances (Economist, 2024). India's vast imports of oil and gas challenge public finances when fossil-fuel prices spike, as when Russia invaded Ukraine. Investing in local production and installation of solar PV panels involves public finances that are less dependent on geopolitical factors beyond the control of India. Unfortunately for the energy transition, so does locally-mined coal. Coal also meets the goals of local finances, energy security, and baseload power. Only political will to put decarbonization at the top of the agenda will reverse this trend. As a result, we see attractive financing terms for both new coal and new renewables in the near- to mid-term future in China and India.

Development aid perception and reality

Most of the energy funding in low-income countries, like in Sub-Saharan Africa, comes from commercial and public finance. The perception some may have that these regions finance most of their energy investments with foreign development aid and concessional finance is wrong. Less than 20% of total energy investment is financed through development finance institutions. That said, the overall access to capital from both development finance and commercial finance in these regions is the bottleneck for accelerating new

Africa currently attracts just 3% of the global investment in energy. New risk mitigation products and increased developmental finance is needed to address the high cost of capital for new clean energy projects in Africa.

energy investments. This lack of sufficient available capital is reflected in our model assumptions with high CoC for new clean energy investments. Furthermore, risk-mitigation products and increased development finance to these regions are required to reduce this finance barrier and would directly benefit the development of new clean energy. COP29 this year places this financing bottleneck centre stage and is sometimes referred to as the 'finance COP'. Countries face the difficult task of agreeing on a new collective quantified goal for providing climate finance from higher-income regions (Henderson, 2024).

The regional picture for energy investments

The transition away from fossil fuels will greatly affect the regional distribution of energy investment in our Outlook, as renewable power is more closely associated with local investment than fossil fuel energy.

However, as shown in Figure 5.3, investment will remain relatively concentrated: three regions, North America, Middle East and North Africa, and Greater China, will represent half of energy investment from 2021 to 2050, though for very different reasons.

After decades of growth, investment in upstream oil and gas will decline in all regions because of declining demand globally. Future distribution of oil investment reflects that forecast, with production increasingly concentrated in regions with lower production costs, in particular Middle East and North Africa. Gas investments will remain more distributed, albeit declining in most regions, with North East Eurasia standing out as the primary investor.

North America will probably experience the most spectacular transition. Investment in oil and gas production will decline by 70% in the 2030s compared with the 2020s, while investment in renewable power will more than double over the same interval. With this transition, North America will be the second region for renewables investment, and the first for grids.

Greater China will be by far the leading region in renewables in the 2020s. The already high penetration of solar PV at the end of this decade will lead to a decline in capacity additions in the 2030s but, overall, China will keep its position at the forefront of investment in solar and wind.

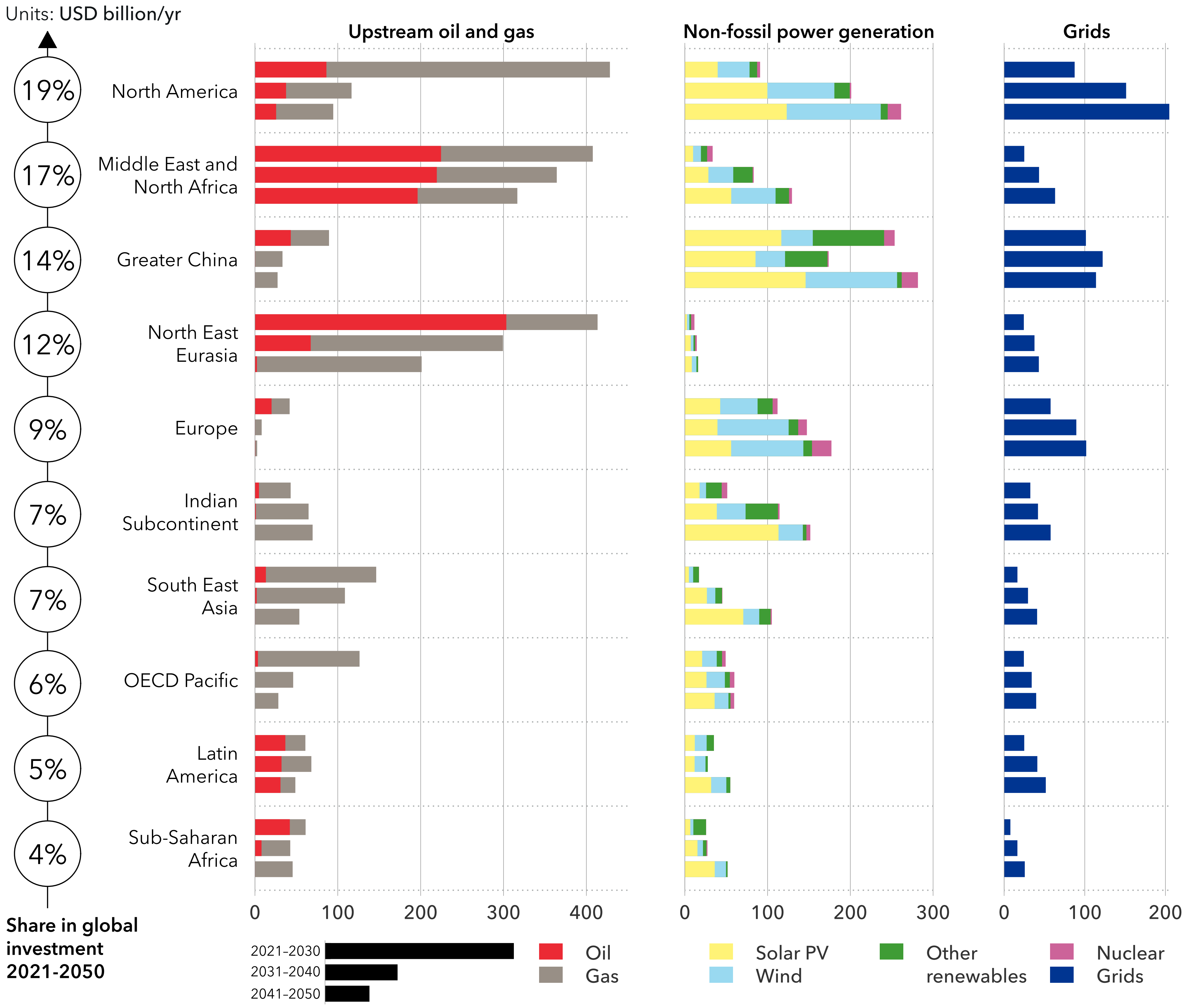
> Greater China will be by far the leading region in renewables in the 2020s.

Europe will be the region with the least investment in oil and gas production, but third in renewables. Wind in particular will stand out as the major sector, with Europe leading investment in the 2020s and 2030s until North America catches up in the 2040s.

Investment in non-fossil energy and grids will increase in all regions, although with different pace and magnitude. This highlights that whatever the political situation or attitude towards climate-change mitigation, the energy transition is also an economically viable one that will attract investors all over the world.

FIGURE 5.3

Average yearly investment in the energy system by region



5.4 COST OF CAPITAL

A major cost driver in energy investment

CoC is a key cost driver for capital-intensive projects like new power generation projects, power grid buildout, and gas infrastructure. It is also critical for end-use sectors like buildings equipment and zero-emission vehicles. Our CoC assumptions should accurately reflect both the impact of debt and equity costs on technology competition and the opportunity cost and risk associated with the investment choice.

Our Outlook includes assumptions about today's CoC per technology, per region, and, importantly, the speed and direction of capital reallocation between technologies up to 2050. This is a challenging task because it requires answers to questions like: 'How does inflation impact the borrowing costs across geographies?', 'Who finances new energy investments and at what cost?', and 'Are companies that reduce their emissions in line with net zero rewarded by the capital markets with a lower CoC?'.

Short term – inflationary pressure impacts the cost of capital

The years of abundant, low-cost capital that chased a small number of renewable energy projects have been replaced by a more complicated risk picture. Inflation increases risk-free interest rates, so its impact on the cost of debt is similar for all technologies. However, the impact of the increased cost of capital does not have a uniform effect on emerging technologies and markets, vs. mature technologies: immature technologies and markets typically see a longer period between the time of the capital investment and first operational cashflows. Higher cost of capital and therefore discount rates therefore lowers the value of an immature technology, vs a mature technology, all else equal. Similarly, higher interest rates have different impacts on fossil vs renewables: the impact on LCOE is larger for renewables, due to its larger component of upfront fixed costs, and lower component of operational expenditures.

During 2023, the CoC for new energy investments jumped in many parts of the world. This was driven by inflation pressure and central banks increasing their steering rates. Banks and investors have now revalued their portfolios and borrowing costs are elevated across the entire energy value chain. The soaring costs for offshore wind companies in Europe and the US are primarily explained by the sudden increase in borrowing costs in these geographies, that result in deteriorating margins, contract renegotiations, and delayed investment decisions. We observe inflation is now more under control, and that our assumptions from last year are largely extended to 2024, based on interest-rate forward curves.

Meanwhile, Greater China faces the opposite risk to Europe and North America: deflation. After lowering interest rates in 2023, China's central bank did not change the steering rates during 2024 and consumer prices are only slowly increasing by around 1% per year, though still under the bank's target of 3%. As a result, borrowing costs in this region are not affected by the inflation worries in many high-income regions across the world. These regional differences in central bank behaviour directly steer borrowing costs and thereby the cost of new energy alternatives for end-consumers across regions.

This underlines the importance of having an accurate CoC assumption that distinguishes between geographies and technologies. DNV has reviewed policy rates and inflation development in all regions to account for this mix of signals that impact borrowing costs. Based on forward curves from central banks, we predict that the impact of inflationary pressure on CoC will be short-lived and fade away by 2030.

Long term – risk perception drives the cost of capital

In the long term, our CoC aims to accurately reflect how debt and equity costs affect intra-technology competition and the opportunity costs and risks associated with investment choices.

The main driver for these variables is risk perception, which varies by region and technological and commercial readiness. Higher risks should be rewarded with higher returns; there is a higher chance of bankruptcy and losses are higher when a bankruptcy occurs because there are fewer and less tradable liquid assets which results in lower valuations in distressed situations. These factors will change over time. Less mature technologies, like renewable hydrogen production, will be less risky in 2040 when technology has matured and been proven in both production and end-use sectors. As market and business cases mature, the lower perception of risk will result in cheaper borrowing costs, lower equity-return requirements from investors, and higher leverage, all off which will drive down the CoC. Understanding these dynamic factors is key to setting assumptions on the CoC for the mid to long term.

What is cost of capital?
The cost of capital (CoC) is the minimum return a company needs to earn on its investments to justify the cost of financing them. It 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

3) The debt-to-equity ratio – often referred to as 'leverage'

Cost of capital predictions

We categorize CoC assumptions under several technology categories as explained below.

Mature renewables

Technologies like solar and solar+storage, onshore wind, biomass, and hydropower.

Since 2021, all regions except Greater China have seen an increase in risk-free rates due to increases in steering rates by central banks. With high debt ratios in the category of mature renewables, we evaluate the impact of increased borrowing costs at around 1.5% between 2022 and 2023. This contrasts with emerging renewables, where increased borrowing costs have a slightly milder impact due to lower leverage. Following forward curves from central banks, we assume an inflationary impact until 2025 that will taper off towards 2030. Our forecast assumes that CoC for these technologies will fall to between 5% and 9% by 2040, differentiated by country risk premiums, and then stay constant through to mid-century.

Immature technologies and markets

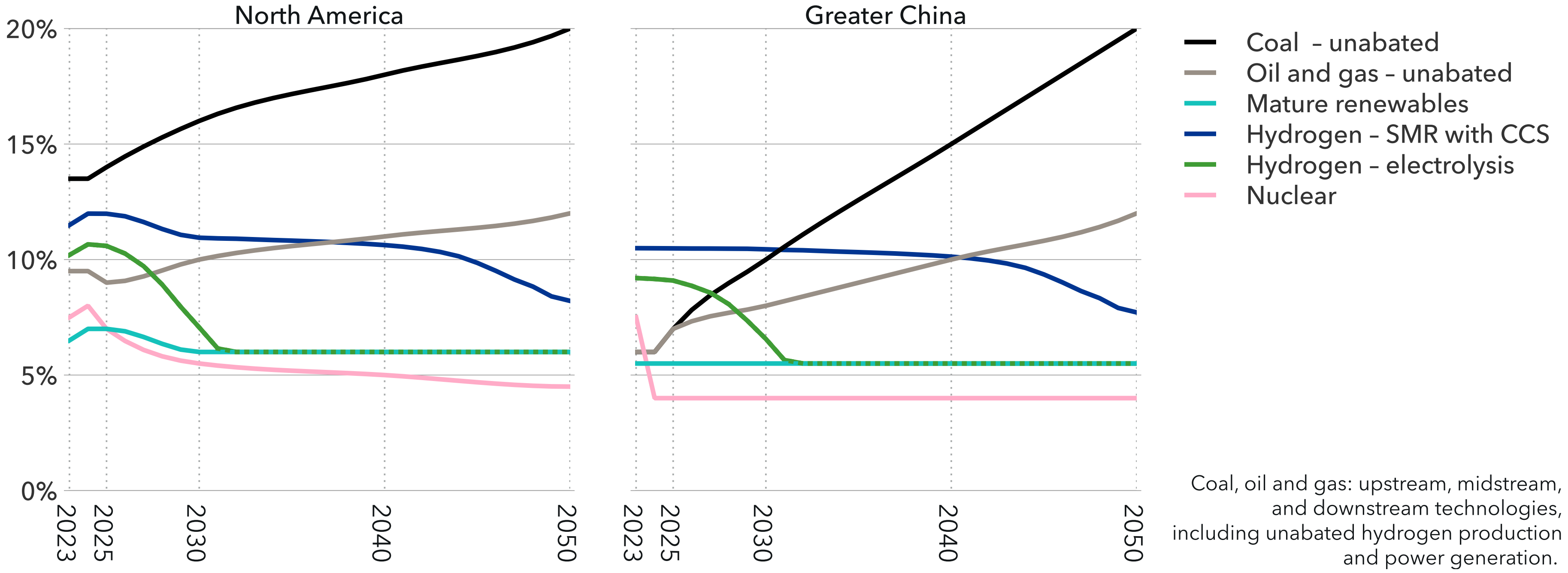
Technologies like (floating) offshore wind, grid-connected and dedicated electrolyser-based hydrogen, geothermal power, and production of sustainable fuels.

We recognize that risks reduce when installed capacity of a certain technology increases. This means that CoC assumptions is set by the available markets, deployment rates of technology, and policy mechanisms. The CoC therefore depends on the model results, and more specifically on accumulated capacity per region for a given technology. This year, we have set CoC assumptions per region for fully immature and fully mature technologies, with a linear development in between. Our CoC assumptions range from 10.5% to 16% for immature, and 5% to 8% for fully mature technologies. Our model dynamically selects the most fitting assumption, depending on technological maturity.

FIGURE 5.4

Development of cost of capital in selected regions

Units: Percentages



Coal, oil and gas: upstream, midstream, and downstream technologies, including unabated hydrogen production and power generation.

Oil and gas

Upstream, midstream, and downstream technologies including grey and brown hydrogen and gas- and oil-fired power generation.

We expect oil and gas in 2024 to have a higher CoC than mature renewables in all regions except the Middle East and North Africa region, mostly because investors now perceive oil and gas investments as riskier than mature renewables. The Middle East and North Africa region consists of the lowest-cost oil and gas producers, like Saudi Arabia and United Arab Emirates, and investments there are therefore rewarded with attractive financing terms. We expect this risk perception to last over the full forecast period to 2050. CoC inputs for the other regions vary between 6% and 11% in 2024. CoC in these all these regions will see an upward trend towards 2030 and 2040, driven by increased perceived risks and capital moving away from new oil and gas production.

Coal

Coal-fired power generation and production.

Investors in Europe and North America already perceive coal as a significantly higher risk than other fossil-fuels or renewable energy projects, as evidenced by increasingly deviating borrowing costs over the past decade. We do expect growing economies in low- and middle-income countries to continue to finance new coal investments at competitive terms towards the 2030s, after which we expect a rapid increase in risk and therefore CoC, driven by reduced availability of capital in all regions and falling demand for coal. We forecast large variations in CoC between the regions in 2024, ranging from 6% in Greater China to 16.5% in Europe, rising to 20% and 25% respectively in 2050.

Nuclear power

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. Resulting nuclear CoC forecasts for 2024 range from 4% in Greater China to 12% in Latin America and 25% in Sub-Saharan Africa, due to the lack of available capital at the sums required. Towards 2050, we do not expect large deviations; with inflation normalized by 2030 and certain regions developing economically, the range of CoC between regions will be 4% to 15%.

5.5 INVESTMENT AND EXPENDITURE BEYOND ENERGY PRODUCTION

On top of increasing expenditures for non-fossil power generation and grid expansion, we forecast that the energy transition will also necessitate investment in additional technologies that are essential to support decarbonization.

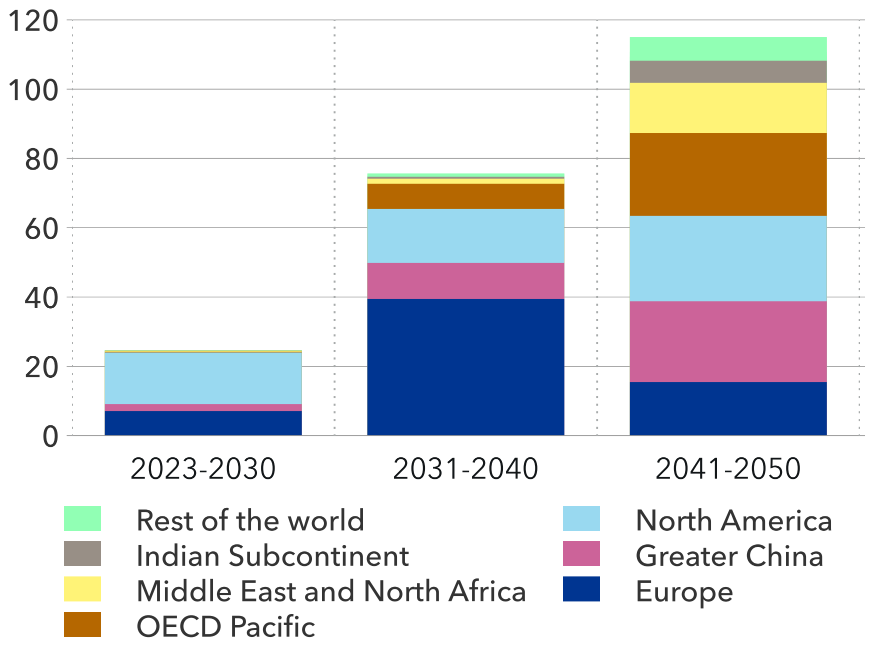
Carbon capture and storage (CCS)

Investment in CCS infrastructure will increase as CSS scales up (for more information on CCS, see Chapter 7). Before 2040, about 80% of this investment in carbon capture will be in Europe and North America, pushed by stricter regulation and/or strong government support (Figure 5.5). Most of the CCS investment globally from now to 2050 will happen in the 2040s, the decade when we forecast abatement technology to really take off. However, Total carbon capture investment is small. Investment in wind and solar was higher in 2023 than the cumulative investment in land-based carbon capture will be over our entire forecast period. This illustrates the differing attractiveness of investment between a profit centre, like low-carbon power generation, and a cost centre like CCS.

FIGURE 5.5

Cumulative investment in land-based carbon capture by region

Units: Billion USD



Electricity storage

Investments in electricity storage will be essential to support the increasing amount of variable renewables on the grids. Investments in standalone, utility-scale Li-ion battery storage showcase the increased interest for this emerging solution (Figure 5.6). Before 2040, investment will be evenly distributed between Europe, North America, and Greater China, which will together account for almost 90% of global investment in electricity storage. As the shares of solar and wind increase in other regions in the 2040s, investment will progressively diversify.

Upstream and downstream investment for clean technology

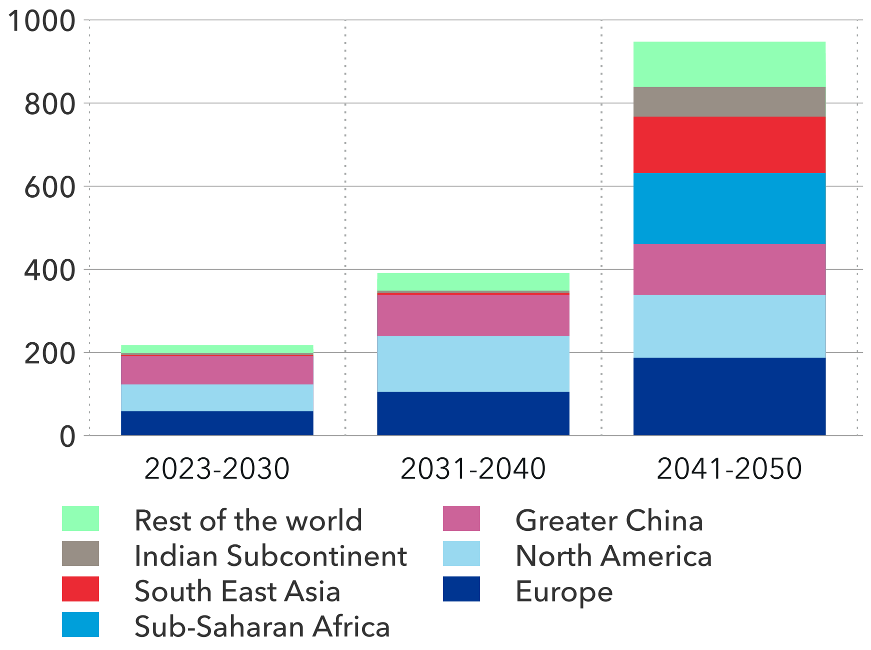
Advancing modern energy systems depends on considerable upstream investment in manufacturing, mineral extraction, and R&D, as well as downstream investment in energy-consuming equipment. While these factors are not explicitly quantified in our forecast, they play a critical role in the dynamics of the energy transition.

For cleantech manufacturing, the current picture is that China stands out as the major investment destination globally, with very favourable financing conditions. The low CoC in China influences not just the deployment of energy assets, but also the entire supply chain. This, along with robust government backing including state-directed R&D, funding for investment, and tax incentives, enables Chinese renewable technology to be competitively priced on a global scale and is a primary driver of China's leadership in cleantech industries.

FIGURE 5.6

Cumulative investment in new utility-scale Li-ion storage assets by region

Units: Billion USD



With investment reaching USD 890bn in 2023, China's clean-energy industries such as solar power, electric vehicles, and batteries matched almost all worldwide investment in fossil-fuel supplies that year (Myllyvirta, 2024). China is also leading investment in emerging renewable energy technologies, such as electrolysers for renewable hydrogen, capturing nearly half of the total global investment from 2020 to 2022 (IEA, 2023).

Yet, China's dominance is facing growing resistance as several regions aim to reduce their dependence on it for supplying these technologies that are deemed increasingly vital for national security (see the Manufacturing section in Chapter 1). Overcapacity and current projects mean that China will still have a leading role in most sectors to the end of this decade. However, most investment in battery manufacturing could take place in Europe and North America from as early as 2025 (Fu et al., 2024).

Mining of critical minerals (e.g. lithium, nickel, cobalt) has also attracted significant attention in recent years. Investment in critical mineral mining is more unstable, as it is very dependent on commodity prices. However, it has more than doubled since its low in 2006, reaching USD 50bn in 2023, with lithium displaying 60% growth that year (IEA, 2024c).

On the downstream side, we also expect investment in energy efficiency in buildings, transport, and industry to reach a new all-time high above USD 600bn in 2024. Approximately 75% of global end-use investment is concentrated in China, Europe, and the US (IEA, 2024a).

Is a globally just transition achievable?

In our view, a just transition is broadly achievable from a purely financial perspective. As shown in Figure 5.1, energy expenditure becomes an ever-smaller percentage of global GDP in our forecast period, falling from 3.3% in 2023 to just 2% in 2050. In theory, the savings implied by this shift are more than adequate to cover the costs of a just transition, whether that involves local support to fossil fuel workers and/or substantial support from high-income countries for the energy transition in low-income countries.

In its report, *Seven principles to realize a just transition to a low-carbon economy*, the Stockholm Environment Institute (2020) states the first principle is that a just transition should actively encourage decarbonization and must not be used as an excuse for delaying the transition. The authors argue that delaying the transition, which has globally agreed goals, is itself unjust, not least for those most vulnerable to climate change both now and among future generations. We add to this argument that delaying the transition also delays the realization of an efficient energy system. If the fossil fuel industry is unable or unwilling to use its current profits to fund the retraining, relocation, and early retirement costs of its workforce, then the prospect of substantial future savings from an efficient, electrified energy system should give governments encouragement to socialize the costs of a just transition over time.

This is not, of course, an argument for the abrupt and unplanned termination of fossil fuel sources and uses. One consideration is that the retraining of fossil fuel employees is something that takes time, with the best approach being a mix of short, high-intensity retraining/upskilling courses and formal, tertiary education programmes (Wilcock, 2022). This approach gives superior productivity outcomes for society and welfare outcomes for the individual employees compared to early retirement packages or lump-sum termination payouts.

Energy justice framework

Although the concept of a just transition is widely used to advocate for better people-focused outcomes in the energy transition and in climate action, there is no universal definition. This lack is because the perception of justice is highly dependent on contextual factors like location, income, energy access, and political system. Energy justice is also perceived differently within and between countries and regions.

The energy justice framework describes justice as resting on three pillars:

- **Distributional justice** identifies the inequalities of distributing burdens and benefits of the energy transition.
- **Justice as recognition** concerns the fair and free inclusion of all those who will be affected or involved in the energy transition.
- **Procedural justice** comprises access to information and participation in relevant decision-making processes (Jenkins et al., 2016).

People, workers, and communities which have measures and support spanning the three pillars of energy justice are more likely to have just outcomes from the energy transition. We discuss the framework in the context of societal pushback against the energy transition in Chapter 6.

Regional policies targeting just transitions

Achieving just outcomes requires policies to address all three pillars of the energy justice framework, and must place people, workers, and communities at the centre of the energy transition conversation. The concept of a just transition is gaining traction with governments worldwide: as of late 2022, just-transition principles were reflected in 38% of 170 nationally determined contributions (NDCs) and 56% of 52 long-term, low-emission development strategies (LT-LEDS) submitted to the UN (UNDP, 2022).

A prime example of domestic policy is the EU's *Just Transition Fund*, which provides financial support to regions, sectors, and communities within EU member states that are severely affected by the energy transition. The fund aims to address distributive inequalities between countries in a region, recognizing that some locations are more affected than others. In Ireland, for example, funding will focus on the Midlands, which is grappling with the closure of peat-reliant power stations. An example of foreign policy is the *Just Energy Transition Partnership* (JETP) joint initiative financed by the EU, France, Germany, the UK, and the US, which supports the energy transition in Indonesia, Senegal, South Africa, and Vietnam. JETP recognizes that there are inequalities between countries globally, demonstrating the flow of finance from high- to middle- and low-income countries.

It is not possible to forecast the degree to which just transition plans interwoven in the NDCs will come to fruition or how deeply the transition will be characterized by such principles. However, we re-iterate our finding that a comprehensive transition to technologies such as solar, batteries, and wind power is likely to save the world economy substantial amounts of money relative to a fossil fuel dominated system, and that should provide substantial room to manoeuvre towards a faster, and more just, transition.

Highlights

This chapter explores policies that impact the energy transition. It covers global COP28 initiatives and regional and country-level developments in climate, energy, and industrial policies.

We discuss five prominent developments that globally frame transition dynamics and affect the transition.

We outline our view on a policymaker's toolbox with available policy options to advance the transition.

We demonstrate the policy toolbox across high-, middle-, and low-income regions in the Outlook and outline policies in selected energy supply and demand sectors, focusing on developments since last year's forecast.

Finally, we explain how policy considerations exert influence in three main areas, and how each of the 12 policy factors are incorporated into our analysis.

6

POLICY

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6.1 POLICY AND THE ENERGY TRANSITION

This chapter details policies impacting the energy transition and how we incorporate policy factors into our forecast. These factors include a wide range of technology-push policies designed to reduce the cost of clean technology, demand-pull policies aimed at stimulating demand for clean energy, and policies that are delaying the transition – such as fossil-fuel subsidies and a lack of carbon pricing. We also explore the socio-political context affecting policy implementation, including societal pushback and consumer wariness of disruptive change and the geopolitical 'polycrisis' distracting governments from implementing rapid, coherent energy policies. We are deeply aware that our forecast sees the world falling severely short of meeting the aims of the *Paris Agreement* and that this will largely be due to policy failure. To comprehensively address the climate emergency, as outlined at successive COPs, governments need to pull all possible policy levers to scale and accelerate the transition.

On publication of this edition of our Outlook in October 2024, there will be barely five years left for the world to achieve the science-based emissions thresholds set out by the IPCC (2023). CO_2 emissions need to be approximately half of 2019 levels by 2030 and GHG emissions must be cut by 43% by 2030 and 60% by 2035. Instead, global energy-related CO_2 emissions grew in 2023. Targets are hanging by a thread and the warming trend is clear. Data from the Copernicus Climate Change Service showed the warmest June on record in 2024, marking the thirteenth month in a row in which the global average temperature reached a record value for the month in question – a stark warning that more ambitious climate action is needed (Copernicus, 2024).

Ongoing, linked, and cascading ecological and climate risks are borderless problems that require cooperation. However, fracturing geopolitics are interfering with the ramp-up of the joint efforts and expenditures needed to achieve climate and sustainable development goals (SDGs) by 2030. State budgets are being rebalanced to military demands. Severe weather events are becoming more frequent – storm damage accounted for 76% of USD 250bn losses in 2023 – sending public budgets into repair mode (MunichRE, 2024; Swiss Re Institute, 2024).

> To comprehensively address the climate emergency, governments need to pull all possible policy levers to scale and accelerate the transition.

Nevertheless, the first Global Stocktake finalized at COP28 in the United Arab Emirates and the UAE Consensus reaffirmed global commitments. The Stocktake will inform the next round of nationally determined contributions (NDCs) under the *Paris Agreement*, to be submitted by February 2025. COP28 sought to instil an action agenda and launched key initiatives which are highlighted on the next page.

A selection of COP28 initiatives

- The *UAE Consensus*[1] outlines 'transitioning away from fossil fuels in energy systems' in its mitigation text (28d). The *Oil and Gas Decarbonization Charter*[2] agrees to zero methane emissions by 2030 and net-zero operations by 2050 at the latest. This was affirmed by 31 national and 21 international oil companies, representing 40% of global oil production.

- The *Global Renewables and Energy Efficiency Pledge*[3], commits to triple installed renewable energy generation capacity to at least 11 TW by 2030 and to double the global average annual rate of energy-efficiency improvements from around 2% to over 4% annually until 2030. This was signed by 124 countries.

- The *Declaration to Triple Nuclear Energy Capacity by 2050*[4] was announced by France and the US and is endorsed by 22 national governments.

- The *Hydrogen Declaration of Intent*[5] aims to develop a global market for renewable and low-carbon hydrogen and hydrogen derivatives through mutual recognition of certification schemes and international methodology (ISO/DTS 19870) for greenhouse gas (GHG) footprint assessment.

- The *Joint-Agreement on the Responsible Deployment of Renewables-based Hydrogen*[6] was advanced by the UN Climate Champions in response to the *Hydrogen Declaration of Intent*. It aims to set clearer thresholds on what qualifies as 'clean' hydrogen and includes a pledge to prioritize renewable hydrogen.

- The *Industrial Transition Accelerator*[7] targets high-emission industrial subsectors to turbocharge the pipeline of industrial decarbonization projects to reach final investment decisions by 2026 and operations by 2030. It is backed by Bloomberg Philanthropies and the COP28 Presidency and is hosted by the Mission Possible Partnership.

- The Industrial Deep Decarbonisation Initiative's[8] *Green Public Procurement pledge* (GPP) aims to create market demand and drive heavy industry decarbonization, starting with steel, cement, and concrete. It is advanced by the governments of Canada, Germany, the UK, and the US, and endorsed by Japan, Austria, and UAE.

COP28 ©UN Climate Change/Christopher Pike

[1] UNFCCC (2023)
[2] COP28 (2023a)
[3] COP28 (2023b)
[4] OECD-NEA (2023)
[5] COP28 (2023c)
[6] Climate Champions (2023)
[7] MPP (2023)
[8] IDDI (2023)

We continuously map, track, and assess global, regional, and national proposals and law-making for their likely transition impacts. Policy inputs to our forecast are illustrated in Figure 6.1 and described in more detail in Sections 6.3 and 6.4, where we discuss policy developments and provisions since last year's forecast.

FIGURE 6.1

Policy factors included in our Outlook

Recent framing developments

DNV has observed five prominent developments affecting global transition dynamics since last year's ETO.

1. DIFFERENT PRIORITIES ARE BATTLING FOR ATTENTION AND SPACE

Climate and energy transformation need to find a place among other competing objectives and immediate challenges; nature and biodiversity loss linked to the energy transition also competes for policy attention. At COP28, the *Joint Statement on Climate, Nature and People* (COP28, 2023d) affirmed that the 2030 *Paris Agreement* goals and the *Kunming-Montreal Global Biodiversity Framework* cannot be achieved without urgently and coherently addressing climate change, biodiversity loss, and land degradation. The climate crisis needs to be averted together with the nature crisis.

Achieving the aims of the UN *Biodiversity Agreement* 2030 means maintaining, enhancing, and restoring ecosystems. The UK is a front-runner that exemplifies likely future requirements. It has adopted a mandatory 10% biodiversity net gain approach for projects to deliver better-quality natural habitats than before developments. The EU's *Nature Restoration Law* (EC, 2023a) will similarly expand scrutiny from a nature perspective. We see regulatory developments in solicitation processes for offshore wind in the US and European countries to advance net-positive biodiversity goals (James et al., 2023) and in negotiations of non-price criteria (e.g. sustainability and cleantech resilience contribution) in renewable power auctions as part of the EU *Net-Zero Industry Act* (EC, 2024). Project developers will have to consider broader societal objectives beyond price levels in procurement procedures, which is likely to make projects more costly. Mitigation projects to prevent the climate and nature crises will have to go hand in hand because acreage is in high demand for power generation, energy infrastructures, mining, carbon sinks, and biodiversity purposes. We discuss biodiversity in more detail in the highlight in Chapter 3.

Litigation to settle these diverse priorities is on the rise (Setzer et al., 2024). Courts are increasingly called upon to establish accountability for climate losses, pollution, and rights of indigenous people. However, the litigation space also includes cases that are not aligned with climate and nature goals such as: ESG backlash, lawsuits against activists to deter climate agendas, just-transition cases on the distributional impacts of climate policy, and green-versus-green cases concerning trade-offs between different environmental aims. Besides litigation trends, policymaking will be empowered by data availability, such as from satellite imagery of biodiversity and supply-chain mapping, and the promise of AI becoming a tool to support action to understand and reverse losses (UKCEH, 2024). We have seen front-runner companies committing to voluntary frameworks and self-regulatory action, but the number of companies setting biodiversity targets is still far below climate targets (Harfoot et al., 2023).

2. PRICE SPIKES AND SOCIAL IMPACTS SHAKE THE TRANSITION

Public attention to climate and environmental challenges fluctuates in the face of new shocks. The People's Climate Vote 2024 – a survey from the UN Development Programme (UNDP, 2024) – reveals a strong global consensus with 80% of respondents supporting more ambitious climate action. However, shocks in recent years, like energy price swings induced by the pandemic followed by demand rebound and Russia's war on Ukraine, have had world-wide ripple effects on current public attitudes and hesitation towards deeper climate action. The Israel-Hamas-Hezbollah conflict has added to energy affordability concerns and raised the threat of regional conflict in the Middle East, potentially undermining global fossil-energy supplies from the world's chokepoint for fossil fuels. Further regional escalation will determine the future risk premium in the oil price. So far, market sentiment around the prospect of peak and waning oil demand seems to have counterbalanced price surges.

Spikes in both energy and food commodity prices spill over to exacerbate the cost of living. Fossil-fuel subsidies have increased dramatically to ease the crunch on consumers and mitigate high energy costs on households and firms (OECD, 2023). Such subsidies almost doubled in 2023 to more than USD 1.4trn across the OECD and partner countries. This practice has several ramifications, including draining public budgets and preventing the acceleration of energy substitution and/or energy-saving measures. While the World Bank's global commodity price index reported decreasing prices in key commodities, it also found that risks of increasing food prices remain high and reported a continued demand surge and price pressure in copper and nickel, propelled by investments in clean energy infrastructure (Baffes et al., 2024). In combination with upfront costs required by the energy transition, there are fertile grounds for argumentation, even misinformation, about climate policy and the costs of energy transition being too high (Ward, 2022). We argue the opposite: the overall result of the energy transition will be substantial economic gains in the long term (Chapter 5). This position is in line with analyses by the IEA, the Rocky Mountain Institute, and Oxford University, each of which present evidence about the affordability of the transition (IEA 2023a; RMI 2023; Way et al., 2022).

> Responsible policy design will have to prioritize the well-being and interest of communities if it is to win over opposition to energy transition projects.

In the short term, however, the need for government attention on transition impacts on at-risk populations cannot be emphasized enough. Responsible policy design will have to prioritize the well-being and interest of communities if it is to win over opposition to energy transition projects. Recently, German and EU Parliament elections showed that a successful energy transition policy is a key instrument against extremist forces (Wehrmann, 2024). The EU Social Climate Fund to accompany the carbon price implementation in Europe's building and road sectors (emissions trading system ETS-2 scheme) and the EU Just Transition Fund (supporting territories affected negatively by the transition) are illustrative of policy design that seeks to address unjust impacts and prevent climate policy from exacerbating social and political divisions. Additional measures will likely be implemented to buffer the higher financial burden on low-income households against high-demand pricing as time-variable electricity pricing sees further penetration. For example, rising block tariffs (with different charges depending on how much electricity is used) could be used to force wealthier households to contribute towards the cost of providing subsidized services to poorer households and incentivize wealthier users to invest in energy efficiency. We discuss social aspects of the energy transition in more detail in the highlight (see page 134) and specify how our forecast accounts for societal pushback to renewable electricity projects in ETO regions.

3. GOVERNMENT POLICIES FOR ECONOMIC SOVEREIGNTY

A cascade of trade tariffs on imports and industrial policies marks the policy environment. Governments are aiming to promote specific industries and protect domestic sectors to increase economic sovereignty and competitiveness (Shih, 2023). With cleantech investments surging – expected to hit USD 2trn in 2024 (IEA, 2024) – there is fierce competition for industry and positioning in green value chains, and employment gains in the promised decarbonization markets. In the wake of pandemic disruptions and Russia's ongoing war on Ukraine, governments rebooted efficiency, renewables, and nuclear policies for energy security reasons and diversified fossil-fuel sourcing away from suppliers that use energy as geopolitical leverage. The rising risk of overreliance on single import countries in green value chains has also heightened the focus on counteracting China's leadership and inflow of cheap Chinese cleantech, threatening to outcompete national manufacturing bases, particularly among high-income regions.

Advancing economic competitiveness, industry and 'home-grown' technologies (e.g. EVs, batteries, wind, solar PV) are the end goals of relaxed state aid rules, innovation support, and government investment programmes. Governments are creating an increasingly complex set of policies, including trade tariffs and domestic content requirements to promote 'economic security'. These measures serve domestic interests and provide decarbonization compliance support to domestic industry. Project developers will be required to screen their supply chains for the origins of materials and products in order to meet requirements of these government support schemes. How we consider the impact of geopolitics on manufacturing locations and technology costs quantitatively in this Outlook is detailed in the introductory pages of this report.

4. VALUE CHAINS AND INFRASTRUCTURE

Policy developments increasingly emphasize advancement of national and regional energy value chains and infrastructure (new or repurposed) while considering the emission intensity of low-carbon value chains from upstream emissions to point of consumption. The EUs *Delegated Act on methodology to assess GHG emission savings* is a good example of this (EC, 2023b).

'No transition without transmission' was repeated mantra-like at COP28 in the UAE, and a vast newbuild programme lies ahead. This is recognized in a host of policy packages in the US, China, the EU, and Japan and we discussed it in our *New Power Systems* report (DNV, 2024b). However, value-chain and infrastructure requirements go far beyond the power sector. Hydrogen and derivatives and carbon capture, storage, and removal need investments to enable the physical value chains and trade. Establishing business models where the value-chain activities make economic sense for each player along the chain is still a challenge.

To address this, government funding programmes are giving infrastructure projects – including hubs, ports, terminals, and pipeline networks – ever-more attention and centrality. The US Department of Energy's Regional Clean Hydrogen Hubs Program, the EU's Important Projects of Common European Interest (IPCEI), India's National Green Hydrogen Mission, and Japan's Green Innovation Fund and launch of its Hub Development Support (GR Japan, 2024a,b) are all aiming to scale infrastructure and value chain developments. Different emission-intensity requirements specified in these support schemes and definitions of 'clean' (e.g. in the hydrogen space) will also impact value-chain developments and trade.

5. MOBILIZING FINANCE TO DEVELOPING ECONOMIES

There is increased attention among financial policymakers on raising investments, particularly in emerging markets and developing economies, to get the 2030 *Agenda for Sustainable Development* (climate and SDGs) on track. Although global clean energy spending is at an all-time high (IEA, 2024), the UNCTAD's *World Investment Report* finds a widening investment deficit faced by developing economies to achieve clean energy SDGs by 2030: about USD 1.7trn in renewable energy investments is needed each year, but total investments in clean energy foreign direct investments were only USD 544bn in 2022 (UNCTAD, 2023).

The COP15 collective goal of USD 100bn annual finance from developed countries by 2020 was only achieved in 2022 when they provided close to USD 116bn (OECD, 2024). This level serves as a floor and must be sustained to 2025. A *New Collective Quantified Goal on Climate Finance* (NCQG) for the 2025 to 2030 period needs to be negotiated at COP29 in Baku, Azerbaijan. The gulf between parties in financing negotiations is wide (Henderson, 2024) and this lack of resolve on financial commitments poses a hindrance to ambitious mitigation strategies for the 2025 NDC updates. Unless climate finance, especially grants and concessional instruments, are increased to low- and middle-income regions and aligned with clean energy – earlier phase-out than the economic and operational lifetime of fossil-fuel plants, natural climate solutions, and so on – climate objectives will not materialize.

There are regulatory efforts to close financing gaps and unleash capital investment flows to net-zero assets. Reforming multilateral development banks (MDBs) will reinvigorate their purpose of bringing transformative change and playing a supportive role in managing risks that block private investments and keep the cost of capital high (Chapter 5). This effort was emphasized in the G20 report from the Independent Expert Group (G20, 2023). In the legal landscape, disclosure reform, such as that pioneered by the EU legislative package for financial institutions (ECB, 2023), requires transition planning and transparent disclosures on a variety of sustainability risks. Finally, there is taxonomy development which aims to scale up transition finance and channel private investments towards sustainability objectives by classifying the activities that are taxonomy compliant. There are currently 47 taxonomies in effect or under development, such as in the *EU Taxonomy* and the *ASEAN Taxonomy for Sustainable Finance*. However, the proliferation of taxonomy initiatives, with divergent requirements and reporting obligations, creates market confusion and challenges for cross-border investors and businesses (Spaans et al., 2024). A level of harmonization and an accepted definition of sustainable finance will likely get regulatory attention to avoid additional hindrances to cross-border capital flows.

> Lack of resolve on financial commitments poses a hindrance to ambitious mitigation strategies for the 2025 NDC updates.

How does societal pushback affect the energy transition?

Despite high acceptance of renewable energy in general, societal pushback at a local level has delayed and cancelled renewable power projects around the world, especially in high-income regions. Opposition tends to arise from local communities living near planned project sites. Siting and linked issues like project size, height, and distance from homes are typically the most contentious issues, particularly for onshore wind and solar technologies. Projects that displace or significantly disrupt local communities face the most resistance. These projects tend to be large installations, such as hydropower, nuclear, or coal mines; it is not only new renewable projects that face societal pushback. Projects which utilize advanced public engagement measures experience less resistance. We have incorporated societal pushback to some renewable energy developments into our model, but our scope is limited to utility-scale renewable energy and does not include fossil-fuel or CCS-related projects.

Pushback against renewable energy projects can be due to myriad real and perceived factors such as lack of awareness of renewable technologies, land-use changes, and ecological degradation. The spread of misinformation has exacerbated renewable energy opposition by validating misconceptions around efficiency, availability, energy costs, material use, human health impacts, and impacts on wildlife. Misinformation has also increased distrust of governments and institutions in some regions. Resistance often goes beyond simply 'NIMBY-ism' (not in my backyard) to span concerns around inclusion, fairness, and participation in energy decision-making processes. Valid concerns about nature impacts and infringements on indigenous people's rights and ancestral lands without prior informed consent have added to grievances (Aung, 2020). We explore the topic of biodiversity in the fact box on Page 81 in Chapter 3.

We recognize that public acceptance and the existence of pushback is a regional issue influenced by features beyond engagement. Factors such as political system, regional income levels, and current levels of energy access play a role. Hence, we observe great variation across ETO regions as illustrated in the North America and Indian Subcontinent deep-dives below. Greater China, North East Eurasia, and the Middle East and North Africa, regions which are not dominated by democracies, tend not to have widespread public engagement processes, and hence public feedback is not generally considered in relation to large energy projects. Therefore, we do not consider societal pushback to renewable energy projects as a significant delay factor in these regions. That said, we

acknowledge that non-democratic governments do, however, care about popular support. Hence, impassioned public protests in China's cities in opposition to dangerous facilities like paraxylene (PX) chemical factories or highly disruptive infrastructure (highway, rail) developments have been effective in swaying official decisions (Hu and Han, 2023). Relatively remote renewable installations or grid buildouts which are clearly in the widespread public interest tend not to excite those levels of protest.

Overcoming societal pushback through participatory measures

Projects with more advanced methods of public engagement tend to experience fewer and less intense instances of opposition to planned renewable energy projects. Pushback on projects can be mitigated through public consultation and engagement focused on the communities around the proposed project site. Engagement types can be separated into three levels: basic (communication), intermediate (consultation), and advanced (participation). The levels of public engagement are cumulative; participation models include consultation measures which include communication (Table 6.1). The deepest level of engagement with participatory measures is most useful for fostering public acceptance and successfully implementing renewable energy projects. This is because these participatory measures are rooted in the three pillars of the energy justice framework: distributional, recognition, and procedural (Lacey-Barnacle et al., 2020). Distributional justice encompasses the fair distribution of burdens and benefits (e.g. energy affordability, energy access, and financial compensation for land) and justice as recognition focuses on how to involve and recognize those who are affected by energy developments. Procedural justice revolves around ideas of inclusion, access to information, and participation in the decision-making process, which is the salient theme of societal pushback (Segreto et al., 2020).

ETO regions and pushback

We identified Europe as the ETO region with the most sophisticated and developed measures to manage pushback. An example is the cooperative ownership model in Zeewolde in the Netherlands, where 83 wind turbines are collectively owned by over 200 locals and farmers. Denmark uses compensation schemes, where renewable developments financially compensate local communities and contribute to a green fund which is used for reforestation, public green infrastructure, and citizen dialogues around the energy transition. In the UK, the Brixton Solar Community (an organization of non-profit cooperatives) grants locals cooperative ownership of solar PV on public buildings through a nominal membership fee, empowering them with voting rights in the decision-making processes of the organization (Lipcaneanu and Vela, 2022).

TABLE 6.1

Level of public engagement

	EXAMPLES OF PARTICIPATORY MEASURES
Basic - Communication	**Anticipated outcome of engagement: transparent flow of information on the project process and period**
	– Dissemination of project and developer information in a way that is easily accessible by the local community. Information should include project parameters (size, distance from residences), project timeline, benefits and risks, and energy output. – Clear and simple communication of what the technology is and how it works. This information should come from both the developer and the local government authority. – Assessment of the environmental impact. – Clarity around which government body is responsible (e.g. local, regional, or national).
Intermediate - Consultation	**Anticipated outcome of engagement: provision of public feedback on the project and inclusion of public concerns in decision-making process**
	– Public consultation with the local community before siting is confirmed – via measures like townhall meetings, feedback forums to submit comments physically or digitally, and gauging community interest in the project. – Public consultation with the local community after siting so that locals can provide feedback on size, noise, land use, etc. – Ongoing meetings to keep the community up to date with project progress. – Public consultation to handle conflict and facilitate resolution.
Advanced - Participation	**Anticipated outcome of engagement: distributionally just outcomes where project development contributes positively to the community**
	– Shared/cooperative ownership models where citizens jointly own all or part of a renewable energy project. – Financial benefits (e.g. ongoing income and/or reduced energy prices from the project for local communities) typically through participatory business models. – Provision of jobs for the local community in both the short term (e.g. construction) and long term (e.g. maintenance, administration). – Other community benefits like increased ancillary business activity, implantation of public infrastructure, and developer-led initiatives like protection or regeneration of local land.

Local issues in a global debate: the case of North America

North America is the region with the most delays and cancellations due to community organized opposition. In the US, 53 utility-scale wind, solar, and geothermal projects were either delayed or cancelled in 28 states between 2008 and 2021 (Susskind et al., 2022). Research from the Lawrence Berkeley National Laboratory (2024) found the average unrecoverable cost of a cancelled project was USD 2m for solar and USD 7.5m for wind. They identified local ordinances, grid interconnection, and community opposition as the leading causes of cancellation of wind and solar projects. Many blocked and cancelled projects were due to intergovernmental confusion or disagreement, especially regarding zoning and land-use laws between local and state level. At least 395 local and 19 state restrictions that could limit or block renewable energy projects were enacted in 41 states in the US from 1995 to December 2023 (Eisenson et al., 2024).

Restrictions enacted by local government range from temporary pauses to outright bans on renewable energy development. They are influenced in large part by societal pushback, usually from multiple sources of opposition and typically led by small, vocal groups with intersecting issues. The primary reason for opposition is rooted in real and perceived impacts of the renewable energy project on life in local communities. Political polarization and the spread of misinformation are significant forces for exacerbating existing fears and driving opposition. Common concerns cited in the US include:

- Aesthetic changes to the landscape and impact on agricultural activities
- Proximity to households causing issues with noise and light, potentially reducing property value
- Impact on local biodiversity
- Perceived health impacts from living near turbines and grids

Local government restrictions are often at odds with state-level renewable energy goals and requirements. Amid growing local government restrictions, more than a dozen US states are pursuing state-level policy to simplify the approval process. State-level decision-making will supersede local government restrictions and allow states to approve or disapprove utility-scale projects.

Livelihood over aesthetics: the case of the Indian Subcontinent

The visual impact of renewable energy installations is not a primary issue for local communities in the Indian Subcontinent. The grid is advancing, and opposition to overhead transmission lines in India is generally very low. Unlike high-income regions, which largely grapple with NIMBY-ism and misinformation concerns, India and other countries in low-income regions like Sub-Saharan Africa are more preoccupied with energy access and livelihood. Locals typically see increased economic activity and better infrastructure as the primary benefits of solar and wind projects. These include more local shops, businesses, and jobs, better roads, and more opportunity to sell or lease land for profits greater than agriculture could provide. Access to energy for household uses like lighting, cooking, and heating reduces the domestic burden – which typically falls to women – encouraging women's participation in economic activities (Sovacool, 2012).

While renewable energy projects can provide energy, economic opportunities, and jobs, they can also displace already marginalized communities like livestock herders and small-scale farmers who rely on the land for their livelihoods (Mirza, 2023). Engagement with local communities can reduce these land-use conflicts and provide fairer compensation. Although regions around the world face different challenges regarding renewable energy implementation and pushback, there is a shared desire to have one's voice heard.

How we reflect societal pushback in our forecast

We incorporate societal pushback into our analysis as a construction time delay factor for specific renewable energy technology types and nuclear. The delay factors are tailored to each ETO region and differ across technologies. For example, societal pushback increases the construction time in our model for onshore wind by 58% in North America and 44% in Europe, but 0% in Greater China, North East Eurasia, and the Middle East and North Africa. We also modify the pipeline of capacity additions for these technologies by increasing the percentage of cancellations to reflect real-life consequences of societal pushback. As an example, solar PV and solar+storage pipeline projects see increased cancellation rates in half of our 10 ETO regions, ranging from 24% in North America to around 2.5% in South East Asia. The construction delay factor and the pipeline cancellation rate increases will progressively phase out from 2030 onwards. Regions such as Europe with more sophisticated pushback management measures have earlier phase-out trajectories.

Assessing the energy transition impact of societal pushback builds on both quantitative and qualitative research. Quantification of the impact builds on the findings of the Lawrence Berkeley National Laboratory, which measures average delay times of utility-scale wind and solar projects due to local community opposition (Nilson et al., 2024). The qualitative research for each ETO region considers relevance of the pushback/acceptance phenomenon; types of engagement and use of measures to facilitate public engagement; political systems (e.g. democratic, authoritarian); social trust in public authorities; capacity, targets, and resources; regional income; and energy access.

6.2 THE POLICY TOOLBOX

The clean energy transition requires planning and supportive frameworks that mix technology-push and demand-pull policies tailored to policy goals and complemented by fiscal policies (Figure 6.2). These policies are needed to level the economic playing field between incumbent and nascent industry players such as zero- and low-carbon and the fossil-fuel equivalent. The toolbox's real-world application uses blended policies (policy packages) at the level of sectors or supply chains to create predictable framework conditions that de-risk investments and business engagement in the transition.

> In our analysis, we closely monitor pledges related to the *Paris Agreement* and other announced government targets but do not pre-set our ETO model to achieve them.

FIGURE 6.2

Policy toolbox

POLICY TOOLBOX

GOALS & PRIORITIES

Purpose: Structure and inform national and sectoral policy

- Plans – e.g. Long-Term Low Emission Development Strategies (LT-LEDS), National Energy and Climate Plans (NECPs in the EU) to inform short- and mid-term priorities, policies, and investment pipelines
- Industry, sector agreements – e.g. IMO and ICAO decarbonization targets and strategies
- Public-private partnerships – joint innovation undertakings leveraging private sector resources (e.g. Mission Possible Partnership)

FISCAL POLICIES

Purpose: Integrate goals and level the playing field

- Public budgets and government entities aligning with SDGs, nature or climate goals
- Fiscal measures – (Dis)incentives through taxes and charges that incorporate the cost of environmental services/pollution into costs of products/activities and tilt consumer choices in favour of clean energy (e.g. carbon pricing, energy tax differentiation reflecting effluents and carbon content, fossil-fuel subsidy removal)

TECHNOLOGY-PUSH

Purpose: Stimulate technology development and cost reduction

- Funding support – e.g. R&D, demonstration, investments in production capacity and critical supply chains
- Infrastructure investments – e.g. grids, charging, refuelling corridors, carbon management
- Technical requirements – e.g. emission limits, fuel economy, efficiency standards
- Taxonomy – e.g. eligible sustainability investments

DEMAND-PULL

Purpose: Stimulate demand and incentivize market uptake

- Market requirements – e.g. fuel blending quotas, bans (e.g. ICEs, fossil-fuel boilers), mandates (e.g. renewable energy use targets), and energy/emission intensity reduction targets
- Economic instruments – e.g. investment/purchase and operation incentives (grants, soft loans, ownership benefits, feed-in tariffs, contracts for difference) and clean public procurement
- Mandatory disclosure – e.g. low- or zero-carbon use, fuel-percentages, and lifecycle emissions

How we consider pledges in our analysis

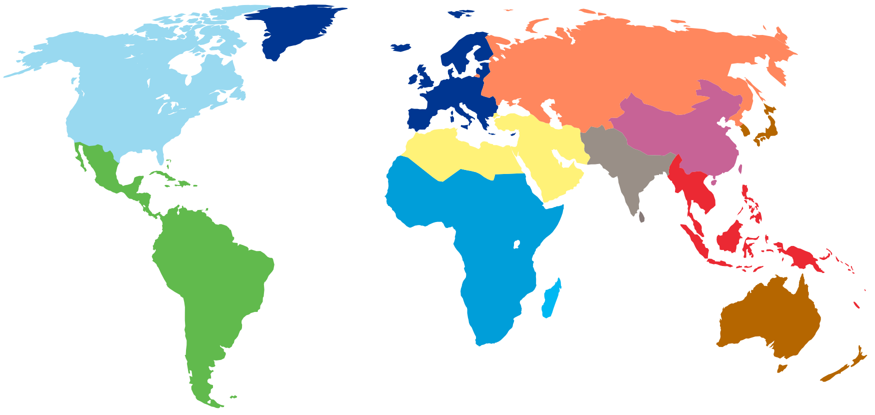
The first Global Stocktake was a key deliverable of COP28. It will inform the next round of nationally determined contributions (NDCs) under the *Paris Agreement* to be submitted by February 2025. Updated NDCs will have a 10-year time frame for a common target date of 2035, address the whole economy in the emission reduction targets, and include all GHGs to bend the emissions curve. Simon Stiell, Executive Secretary of the UN Framework Convention on Climate Change (UNFCCC), emphasizes that these are to be blueprints for economic and social transformation (UNCC, 2024).

In our analysis, we closely monitor pledges related to the *Paris Agreement* and other announced government targets but do not pre-set our ETO model to achieve them. Targets are not always binding, and the key question is: where is the action? At best, target announcements are the initial steps in planning and depend entirely on real policies to back up their implementation. Most countries have inadequate short-term policies despite the boldest pledges.

What matters for DNV's forecast is that policies are both enacted and implemented. In other words, it is target-setting and plans coupled with sectoral policies, supportive measures, and aligned finance and investment that will set the direction, scope, and pace of the transition.

6.3 THE POLICY TOOLBOX AT WORK IN ETO REGIONS

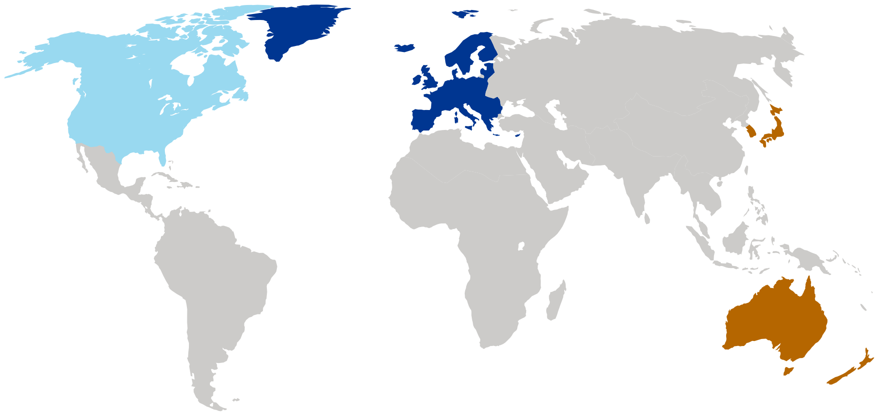
In the next pages, we exemplify the policy toolbox at work in ETO regions with high-level summaries. We then outline select policies in energy supply areas and demand sectors, focusing on developments since last year's Outlook. Policy examples are also given in Chapter 8 covering the energy transition in Outlook regions.



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)



High-income regions

Goals & Priorities

- All high-income regions have mid-century net-zero ambitions, many enshrined in law.
- Several countries have independent science/advisory boards to oversee planning.
- Countries have comprehensive planning, e.g. the EU *National Energy and Climate Plans* (NECP), policy packages, and investment programmes for economy-wide decarbonization.

Fiscal

- **EUR:** Has mature carbon pricing (CP) instruments with an emissions trading system (ETS) complemented by national taxation to incentivize emissions reduction.
- **NAM:** Has CP policy in a minority of US states, while Canada has CP economy-wide.
- **OPA:** Countries have mature CP instruments or are implementing. See carbon pricing Highlight on page 144.
- There are attempts at energy price/taxation reform, e.g. the EU *Energy Taxation Directive*, but these are at an impasse. Ending fossil-fuel support is a long-standing promise (G20 in 2009) but subsidies remain (Tax Policy Center, 2024; Lorteau, 2024; EEA, 2023; OECD, 2023).

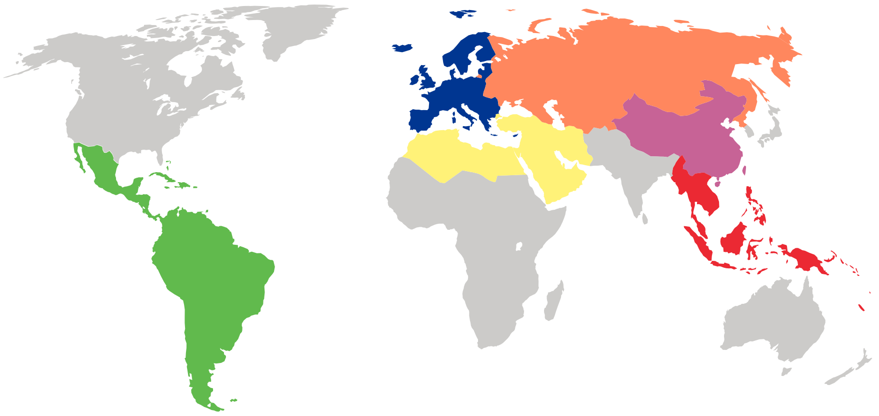
Technology-push

- **NAM:** The US *Infrastructure Investment and Jobs Act* (IIJA) and the *Inflation Reduction Act* (IRA) create federal technology funding programmes and incentives through production or investment tax credits (PTC, ITC). Canada's *2030 Emissions Reduction Plan* provides USD 6.7bn to clean energy investments and manufacturing. A suite of incentives seeks to level the playing field with IRA support.
- **EUR:** European *Green Deal* investments towards energy transition and decarbonization are assessed at USD 359.7bn per year between 2021 and 2030 (EEA, 2023).
- **OPA:** Extensive technology investments are made through South Korea's *Green New Deal* (USD 135bn), Japan's *Green Transformation* policy (USD 987bn), Australia's *Future Made in Australia* (USD 15bn), and New Zealand's *Climate Emergency Response Fund* (USD 2.7bn).

Demand-pull

- **NAM:** Longstanding renewable portfolio / clean energy standard policies for electricity and renewable volume obligations in transport. There are zero-emission vehicle (ZEV) and phase-out policies in road transport prohibiting the sale of new ICE vehicle after 2035 in Canada and 12 US states, and emerging buildings' fossil-fuel heating bans in provinces and states (Vancouver, Quebec, New York).
- **EUR:** Mandatory targets for renewables use set by the *Renewable Energy Directive*. The EU is considering carbon contracts for difference to reduce investment risk and improve the competitiveness of low-carbon alternatives. 23 European countries have announced coal phase out policies, such as by 2033 in the Czech Republic and by 2038 in Germany.
- **OPA:** Japan and South Korea have purchase incentives for EVs and fuel-cell EVs in transport. New Zealand will provide USD 61m in subsidies for green hydrogen consumption.
- **All regions** have green public procurement policies for products such as concrete, cement, or steel products.

The USD values mentioned are calculated from the given local currency at the time of policy announcement with the year-to-date (1 Jan to 1 Sep) average exchange rate to USD. Dates in parentheses signify time of policy/decision announcement where not a reference



Middle-income regions

Goals & Priorities

- **CHN:** China, a front-runner in the global energy transition, is pursuing peak carbon before 2030 and carbon-neutrality before 2060 through its '1+N' policy framework on sector developments.
- **LAM:** Argentina, Brazil, Chile, and Colombia aim to be carbon-neutral by 2050.
- **MEA:** Several countries have net-zero goals from 2050 to 2060. COP27 was in Egypt and COP28 was in UAE.
- **NEE:** Ukraine aims for 65% GHG reduction below 1990 levels by 2030. Kazakhstan, Russia, and Ukraine target carbon neutrality by 2060.
- **SEA:** Most Association of South East Asian Nations (ASEAN) countries have pledged to net-zero emissions by 2060.

Fiscal

- **CHN:** China is revising tax and fiscal frameworks to be conducive to low-carbon development no later than 2030 (MoF, 2022a,b). The national ETS will be a key mechanism in the 'dual carbon control' system (State Council, 2024). The *Catalogue for Guiding Industry Restructuring* aligns investors with national industrial priorities.
- **Several regions** are developing carbon pricing (CP) instruments. In LAM, Brazil, Chile, Colombia have announced ETS schemes. In MEA, Turkey is positioning an ETS at the core of its climate policy. In SEA, Thailand has a tax and Brunei, Malaysia, the Philippines, and Vietnam are considering ETS; Indonesia's ETS has been operating since 2023 which covers coal-fired power; and Singapore, a pioneer, has had a carbon tax since 2019 that covers 80% of national emissions. Fossil-fuel subsidy practices persist in most regions (OECD, 2023).

Technology-push

- **CHN:** Long-term planning permeates the entire energy system with working guidance and targets for R&D and technology developments specified in five-year plans (FYP). Supply-side policy initiatives are indicative of R&D spending and long-term government support.
- **LAM:** R&D spending is relatively low, with Brazil accounting for 62%, equivalent to 1.2% of its GDP (ECLAC, 2024). The *New Industry Brazil* (NIB) policy (January 2024) earmarks around USD 58bn for six missions that include bioeconomy and energy transition. Several governments have designed strategies for green hydrogen supply.
- **MEA:** UAE and the Kingdom of Saudi Arabia (KSA) have ambitious programmes for decarbonization pathways that include renewables, nuclear, green hydrogen, carbon capture, utilization and storage (CCUS) systems, and sustainable aviation fuel (SAF).
- **NEE:** Russia's policies indicate no real commitment to curb emissions (CAT, 2022). Kazakhstan's *Strategy on Achieving Carbon Neutrality* by 2060 (2023) is gearing up renewable power policy to underpin its transformation.
- **SEA:** Singapore is the green economy policy pioneer of the region.

Demand-pull

- **CHN:** Comprehensive policies include improving efficiency (dual energy control: total consumption and energy intensity), setting capacity targets and vehicle shares, advancing electrification, switching fossil-energy use (coal-to-gas, renewable energy, hydrogen), and pursuing industrial upgrading.
- **Beyond the CHN region**, economy-wide decarbonization ambitions and renewable energy policy efforts outside of the power sector are progressing somewhat slowly. Singapore is a notable exception in SEA with its cross-sectoral *Singapore Green Plan* 2030. In MEA, e-mobility policies are taking root, as is buildings efficiency with attention to per capita energy/water consumption.

Low-income regions

Goals & Priorities

- **IND:** India is committed to net-zero emissions by 2070 while Pakistan has proposed a 2050 net-zero target. India has sector plans, but these are siloed, lacking holistic planning. Investment programmes aim to deliver on technology goals.
- **SSA:** Tanzania and South Africa have announced 2050 net-zero targets, Ghana's *Energy Transition and Investment Plan* (September 2023) aims for net-zero emissions by 2060 (previously 2070). Nigeria plans for net-zero emissions by 2060, and Uganda by 2065. Plans seek to tackle energy poverty, deliver on SDG #7 by 2030, pave the way for net zero, and provide energy for industrialization and economic growth.

Fiscal

- **IND:** India plans a carbon market by 2026. Pakistan has preparatory ETS work. Fossil-fuel subsidies in the region result in negative carbon pricing but are motivated by energy affordability in retail pricing. For example, in India (IISD, 2024) and Pakistan's subsidies on energy products accounted for 2.6% of the country's GDP in 2020 (WB, 2023).
- **SSA:** South Africa's carbon tax is its single carbon pricing instrument. Countries are positioning for carbon markets under Article 6 of the *Paris Agreement,* as seen in the *Africa Carbon Markets Initiative* (ACMI). Some countries are taking steps towards energy-subsidy reforms (e.g. Angola, the Gambia, Nigeria, and Zambia) to create space for development spending (IMF, 2023).

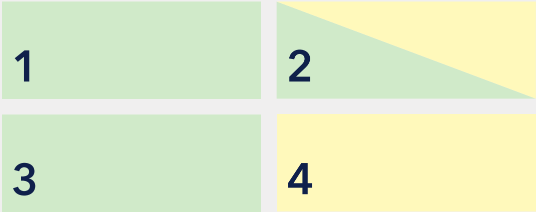
Technology-push

- **IND:** India has national programmes ('missions') in areas such as biodiversity, hydrogen, EVs, and energy storage to position it for manufacturing, along with government funding for technology development and scale up. For example, the *Green Hydrogen Mission* aims for 5 Mt green hydrogen capacity with initial investment funding at USD 2.3bn; the *Production-Linked Incentives* (PLI) scheme to stimulate domestic manufacturing in clean-energy equipment; and the *Strategic Interventions for Green Hydrogen Transition* (SIGHT) programme to 2030 supports green hydrogen and derivatives production. India is also signalling long-term commitment such as the Ministry of New and Renewable Energy releasing (2024) guidelines for incentives with financial outlays through 2030.
- **SSA:** Energy transition and investment plans, for example by Ghana (September 2023) and Nigeria (August 2022), reflect energy system investment requirements, as opposed to existing domestic policy, to underline financing needs (e.g. about USD 410bn above business-as-usual spending in Nigeria between 2021 and 2060).

Demand-pull

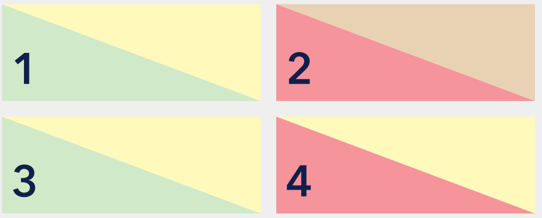
- **IND:** India has several demand-side policies, such as the *LiFE Mission* nudging lifestyle and behavioural changes (e.g. water and energy saving in households); subsidy schemes to encourage e-mobility; targets and renewable purchase obligations (RPO). The Indian government has not signed the *GPP Pledge*, though it has pledged to buy more low-carbon industrial materials to expand the market.
- **SSA:** Policies are aimed mostly towards the power sector and see less progress in energy-demand sectors.

Synopsis on the state of policy



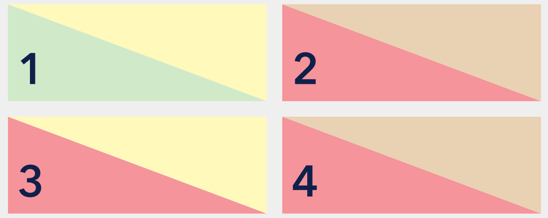
High-income regions

Decarbonization plans. Supply-side policy: technology, green supply chain, hubs and infrastructure investments (all regions). Demand-side policy: uptake measures (EUR). Economy-wide CP (EUR, OPA). Less deployment, demand-side certainty in incentive approach (NAM) given lack of US CP policy. Some fossil-fuel subsidies.



Middle-income regions

Decarbonization plans. Supply-side policy: technology, clusters, infrastructure. Demand-side policy: uptake measures. Expanding CP scope (CHN, China). (Other regions) pre-dominant supply-side policy: technology investment programmes, renewable power focus. Less policy progress on end-use sectors and uptake. CP immature, evolving. Widespread fossil-fuel subsidies.



Low-income regions

Energy expansion plans. Supply-side policy: pre-dominant renewable power focus (IND, SSA). Technology development support (India). Demand-side policy: scarce on industrial decarbonization, but evolving (India). Plans indicative of investment / international funding needs but lacking domestic policy frameworks (SSA). Limited explicit CP, but announced scheme in India. Widespread fossil-fuel subsidies.

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

Policy toolbox

🟩 Well-defined, proven measures
🟨 Defined, partial results
🟫 Early-stage, unclear results
🟥 Insufficient, no results

The synopsis is based on policy toolbox high-level summaries and supply and demand sides, Tables 6.2 to 6.4

TABLE 6.2

High-income regions: A non-exhaustive list of supply- and demand-side policy initiatives, emphasizing the 2023 to 2024 period

Supply-side	Policy levers
Power	– All major economies have signed the COP28 *Global Renewables and Energy Efficiency Pledge*. – NAM: The US and Canada target 100% carbon-free electricity by 2035 and support these goals through tax credits. – EUR: The *REPowerEU* plan aims for a 69% renewable electricity share in 2030. The EU *Electricity Market Design* regulation allows future support through two-way CfDs. – OPA: Future support through competitive tenders and renewable targets in Australia for 82% by 2030 and New Zealand for 100% by 2035. Japan targets 38% renewable and 59% non-fossil generation by 2030, South Korea for 30% renewable and 70% non-fossil by 2038. Both having cap city auctions in 2024 to provide ammonia and hydrogen for co-firing.
Nuclear	– High-income regions signed the COP28 *Declaration to Triple Nuclear Energy Capacity by 2050*. – Willingness to support capacity expansions exists in endorsee countries, for example Canada, Japan, South Korea, the US, France, and the UK.
Grids	– NAM: *IIJA* invests over USD 30bn in US grid infrastructure. Canada's *Smart Renewables and Electrification Pathways Program* has USD 3.3bn to support grid modernization. – EUR: The *EU Action Plan for Grids* (2023) estimates EUR 584bn in necessary investments to 2030, to be prioritized in EU-funded *Projects of Common & Mutual Interest* and benefiting from simplified permitting procedures. – OPA: Australia's Energy Market Operator calls for USD 10.5bn investments into net-zero enabling grids (2024). New Zealand's *Net-Zero Grid Pathways* (2024) approved around USD 243m in investments.
Hydrogen	– NAM: The US *45V* tax credit is tiered to emission intensity and has requirements to hydrogen producers' electricity consumption. The DOE awarded USD 7bn hub-development funding (October 2023). Canada's *Clean Hydrogen ITC* (2024) depends on carbon intensity. – EUR: The *European Hydrogen Bank* supports production capacity with 10- to 15-year CfDs and the *H_2Global* auction instrument will support green hydrogen imports. The list of *Projects of Common Interest* (November 2023) eligible for CAPEX support (maximum 50%) included hydrogen infrastructure-related projects. National funding schemes complement those of the EU. – OPA: Japan and South Korea have hydrogen value-chain funding programmes and are introducing CfD schemes during 2024. Australia allocated USD 1.32bn in the 2023-24 budget to large-scale renewable hydrogen projects through investment support and a production tax incentive starting from 2027.
CCS/DAC	– NAM: *IIJA* provides over USD 12bn for CCS and related activities over a 5-year period and the *45Q* tax credit under *IRA* drives investments. Canada's *Carbon Management Strategy* (2023) is supported by ITCs and CP. – EUR: The EU *Net-Zero Industry Act* (2023) targets annual CO_2 storage of 50 Mt by 2030, and the *Industrial Carbon Management Strategy* (2024) envisions up to 450 Mt by 2050. National support schemes complement those of the EU. – OPA: Japan targets 240 $MtCO_2$ per year stored by 2050 with funding to CCS value chains. JOGMEC selected (2023) seven projects (13 $MtCO_2$ per year by 2030). South Korea aims for 4.8 $MtCO_2$ per year by 2030 and passed the *CCUS Act* (February 2024).

Demand-side	Policy levers
Transport	– NAM: There are federal ZEV purchase incentives in the US and Canada, and also at state and provincial levels complemented by infrastructure funding. The US EPA issued new emission standards (2024). Sustainable aviation fuel (SAF) is supported by policies such as the *Clean Fuel Production* tax credit, the *SAF Grand Challenge* in the US, and Canada's *Sky's the Limit Challenge* and *Clean Fuel Regulations* setting carbon-intensity reduction requirements. – EUR: There are longstanding incentives for EV acquisition or ownership. The EU sets increasingly stringent vehicle emission limits (Euro 7 in 2024) and has a ban on ICE-passenger vehicles/vans for 2035. The *ReFuelEU Aviation Initiative* targets uptake of sustainable fuels while the *FuelEU Maritime Regulation* sets GHG intensity reduction requirements and accelerates demand for renewable or low-carbon fuels. *RED III* sets a binding sub-target of 5.5% for advanced biofuels with a minimum of 1% renewable fuels of non-biological origin. – OPA: Japan and South Korea support vehicle development combined with targets and purchase incentives (EVs, FCEVs). SAF use will increase through mandates, and Japan's *GX policy* provides 10-year tax credits to fuel production. Australia enhanced support to SAF production through *Future Made in Australia* funding.
Manufacturing	– NAM: The *IRA* provides USD 6bn for demonstration and deployment of low-carbon industrial production technologies. Canada's USD 5.9bn *Strategic Innovation Fund – Net Zero Accelerator* supports large industrial emitters adopting clean technology. – EUR: *RED III* (October 2023) sets binding targets for renewables use, requiring an increase of at least 1.6 percentage points as an annual average calculated from 2021 to 2025 and 2026 to 2030. At least 42% of hydrogen used in industry must be renewable fuels of non-biological origin (RFNBO) by 2030, and 60% by 2035. – OPA: South Korea is preparing to introduce carbon CfDs and provides soft loans to large-scale projects in carbon-neutral technologies. Japan will provide around USD 8.5bn over 10 years to support CAPEX in iron and steel, chemicals, paper, and cement (GR Japan, 2024b). New Zealand's GIDI Fund will invest up to 50% of project costs in industry decarbonization. Australia's net zero industrial sector plans are under development (2024) and ARENA funds projects supporting industry transformation.
Buildings	– NAM: The US provides tax credits to electrification. Tax credits for insulation and weatherization of buildings encourage higher building retrofitting rates. Canada has programmes supporting efficiency retrofits, switching to electric heat pumps, latest the *Greener Homes Affordability Program* (2024). – EUR: The EU's *REPowerEU Plan and Energy Efficiency Directive* target a 11.7% reduction by 2030. The *RED III* sets an indicative target for renewables in buildings (49% 2030). The *EU ETS-2* introduces CP on transport and buildings, 2027. – OPA: South Korea supports energy-efficiency retrofits and up to 50% of additional cost incurred in zero-emission new builds. Japan aims for new builds to be zero emission by 2030; the *GX policy* has subsidies for efficiency improvements. Australia's has close to USD 900m in a *Household Energy Upgrades Fund*.

TABLE 6.3

Middle-income regions: A non-exhaustive list of supply-side and demand-side policy initiatives, emphasizing the 2023 to 2024 period

Supply-side	Policy levers
Power	—COP28 *Global Renewables and Energy Efficiency Pledge* signatories include most major economies in LAM; UAE in MEA; Ukraine in NEE; and Malaysia, Thailand, and Singapore in SEA. —CHN: China has a multipronged focus on renewables and flexibility sources. Coal will be phased down by 2030. —LAM: Support through competitive tenders for 15- to 20-year power-purchase agreements (PPAs). Renewable electricity targets range from 20% by 2025 in Argentina to 70% by 2030 in Chile and Colombia. Brazil aims for 45% renewable energy use by 2030 and coal phase-down by 2040. —MEA: Renewable generation targets – Morocco, 52% by 2030 and 80% by 2050; Turkey, 65% by 2035; Egypt, 58% by 2040 – are generally supported through competitive tenders for 20- to 25-year PPAs with state utilities. —NEE: Kazakhstan targets 50% renewable generation by 2050 with support through competitive tenders for 20-year government contracts. —SEA: National energy plans aim to limit coal expansion but lack concreteness on ending unabated coal generation. Thailand's target of 74% renewable generation by 2050 is the strongest in the region. Renewables are mainly supported by FiT and competitive auctions in Malaysia, Vietnam.
Nuclear	—COP28 *Declaration to Triple Nuclear Energy Capacity* by 2050 was signed by Morocco and UAE in MEA; Armenia, Moldova, Mongolia, and Ukraine in NEE. —CHN: The *14th FYP* targets 70 GW installed nuclear capacity by 2025 (55 GW in 2022). —MEA: Nuclear power programmes target expansion, with state assurances and governmental resources backing high capital costs. Turkey aims for 20 GW by 2050 under 'build-own-operate' contracts with nuclear vendor countries.
Grids	—CHN: China's State Grid has announced (2024) USD 70bn in grid networks, aiming for a nationwide supergrid in accordance with the *14th FYP*. —MEA: The Gulf Cooperation Council focus on intra-regional interconnections. KSA's National Grid and Greece's Independent Power Transmission Operator announced a cross-border power link with Europe (2024). —SEA: There is a longstanding ASEAN Power Grid vision but lack of policy harmonization.
Hydrogen	—CHN: The *Hydrogen Industry Development Plan (2021–2035)* targets renewable hydrogen production at 0.1 to 0.2 Mt/yr by 2025. State-owned companies are key investors. —LAM: Brazil and Chile signed the *Hydrogen Declaration of Intent*. Argentina, Colombia, and Chile have production targets. Chile and Brazil announced (2024) forthcoming incentives. —MEA: Egypt, Morocco, Oman, UAE, and Yemen signed the *Hydrogen Declaration of Intent.* Several countries have 2030 hydrogen export targets and government funding (Oman, KSA, UAE) support investments. Egypt's *Green Hydrogen Incentives Law* (2024) provides tax incentives for certain projects (70% investment costs secured from abroad). —NEE: Kazakhstan's hydrogen strategy (2024) targets 10 GW electrolysis capacity by 2040.
CCS/DAC	—CHN: Policies include R&D support, CP, low-cost loans, mandates, and full-chain development through state-owned enterprises like Sinopec and CNOOC. —LAM: Brazil has draft legislation (2024) to establish a federal-level legal and regulatory framework.
CCS/DAC (continued)	—MEA: State-owned entities (Saudi Aramco, ADNOC, QatarEnergy LNG) execute projects and development. Capture/storage targets per year: UAE 10 MtCO_2 by 2030, KSA 44 MtCO_2, and Qatar 11 MtCO_2 by 2035. —SEA: Lack of policy/support to deployment outside oil and gas sector. Malaysia signed an agreement for storing CO_2 from Japan.

Demand-side	Policy levers
Transport	—CHN: China has policy for new energy vehicles and stable support. The hard-to-electrify transport subsectors aviation and shipping have less concerted decarbonization policies (see DNV, 2024a for policy details). —LAM: Brazil focuses on biofuels; its *NIB* policy (2024) aims for 50% in the transport energy mix by 2033, and the *Fuel of the Future* programme (2023) will increase ethanol and biodiesel blends to 2030 and aims to reduce aviation emissions 10% by 2037. Chile, Colombia, El Salvador, and Uruguay are signatories to the *Zero Emission Vehicles Declaration* for new car/van sales globally by 2040. There are some EV-purchase incentives such as exemptions from import tariffs and taxes in Brazil, Costa Rica, Colombia, and in Mexico, which is positioning itself in EV manufacturing. —MEA: Only Israel has a phase-out policy for ICEs (passenger vehicles by 2030). There are increased efforts in EV promotion with uptake incentives in UAE and support for onshore EV manufacturing in KSA. Qatar plans to transition to an emissions-free public transport system by 2030 and Turkey aims to have one million EVs on the road by 2030. —SEA: Biofuel blending mandates in several countries, and growing blend rates in Indonesia (35%) and Malaysia (30%) by mid-2020s (ACE, 2024). ASEAN announced (2023) its EV ecosystem ambition for EV production and uptake. There are incentive packages for EV production. Malaysia, Indonesia, and Thailand offer EV-purchase incentives. Affordability and limited charging infrastructure hamper regional uptake.
Manufacturing	—CHN: The *14th FYP* targets industry upgrading. There are sectoral guidelines for industrial carbon peaking. Electrification is prioritized (2030-2045) and hydrogen (2045-2060) for energy use (NEA, 2023). —MEA: UAE launched (2023) the *Industrial Technology Transformation Index* (ITTI) to accelerate decarbonization and digitalization, also backing the COP28-launched Industrial Transition Accelerator.
Buildings	—CHN: Policies favour coal-to-gas and coal-to-electricity switching. All localities must have coal-substitution projects in urban planning and promote heat pumps and renewables. —MEA: KSA revised its efficiency and retrofitting programme (2024). Turkey introduced (2023) energy efficiency regulation for new builds and 5% renewable energy requirements. The UAE has a new programme (2024) for standards covering energy efficiency, water management, and use of sustainable building materials. —NEE: The Cities Climate Finance Leadership Alliance (CCFLA) Central Asia Hub, funded by Germany, supports investments in energy efficiency, e.g. supporting Uzbekistan's government to meet its 50% improvement target by 2030, where subsidies up to 50% of energy costs negatively influence energy efficiency projects' viability (Bassetti et al., 2024). —SEA: There are some increases in policy, standards, and incentives to improve building energy efficiency and reduce carbon emissions. Examples include the *Energy Efficiency and Conservation Bill 2023* in Malaysia, *Building Energy Code* in Thailand, and the Singapore *Green Building Masterplan* in Singapore.

TABLE 6.4
Low-income regions: A non-exhaustive list of supply-side and demand-side policy initiatives, emphasizing the 2023 to 2024 period

Supply-side	Policy levers
Power	—The COP28 *Global Renewables and Energy Efficiency Pledge* signatories include Bangladesh and Pakistan in IND; and Ghana, Kenya, Nigeria in SSA. —IND: India targets 50% of power from non-fossil sources and 50% of energy needs from renewables by 2030. Pakistan's NDC (2021) targets 60% of all energy production from renewables by 2030. Bangladesh targets a 40% share of renewable electricity by the early 2040s. India's has RPOs on distribution companies, including for 4% energy storage in 2029–2030 (MoP, 2022), however, these companies often fall short of meeting annual targets (Poswal, 2024). Future support through competitive tenders for 20- to 25-year PPA contracts with state utilities, including plans to award 37 GW offshore wind by 2030. Plans indicate new coal additions, and operation of the existing coal fleet for energy security reasons and to meet growing power demand. —SSA: 28 countries in the region signed the COP28 *Global Renewables and Energy Efficiency Pledge*. National targets are common. For example, ECOWAS countries aim for 19% new renewables in 2030. Nigeria for 36% and Kenya for 100% by 2030, the latter with support through feed-in tariffs (FiT). There is a development away from fixed FiT schemes towards competitive tenders, e.g. South Africa aims for long-term PPAs through its *Renewable Energy Independent Power Producer Procurement* (REIPPP) programme. The South African *Renewable Energy Masterplan* (SAREM 2023) aims to add 22.9 GW of utility-scale renewable energy and battery storage by 2030.
Nuclear	—IND: India plans to triple its present installed nuclear power capacity of 7,480 MW to 22,480 MW by 2031 or 2032.
Grids	—IND: India has a single grid network connecting the country. *The Green Energy Corridor Phase II* intra-state transmission system project with an estimated cost of USD 30bn, was approved in October 2023 to enable the 500 GW non-fossil electricity capacity target by 2030. —SSA: The first African *Continental Master Plan* for electricity generation and transmission (one grid for one continent) was endorsed by the African Union heads of states (July 2024) as an Agenda 2063 Flagship Project and blueprint for grid expansion. Tackling grid infrastructure deficiencies is a key focus area in international, concessional finance.
Hydrogen	—IND: Supply-side policies are firming up in India, with a renewable H_2 production target of 5 Mt/yr by 2030 with an associated renewable energy capacity addition of about 125 GW. India aims to produce three-quarters of its hydrogen from renewables by 2050. The first auction results for green hydrogen (production capacity capped at 0.45 Mt/yr) and electrolyser manufacturing subsidies were announced in 2024. —SSA: There are limited policy frameworks and funding programmes to support development. Angola, Kenya, Mauritania, Namibia, and South Africa are taking planning steps to become hydrogen exporters, such as the *South African Green Hydrogen Commercialization Strategy* (2023).
CCS/DAC	—IND: India took steps in 2022 towards understanding CCUS technology as a basis to formulate a framework for CCUS policy (NITI Aayog, 2022). —SSA: There is a lack of regulatory frameworks, and no funding programmes support development.

Demand-side	Policy levers
Transport	—IND: In road transport, India has electrification targets (2030) for new vehicle sales supported by its *FAME II* scheme purchase incentives, and its biofuels policy targets 20% ethanol blending in 2025 (vs.12% in 2022–2023). Pakistan's *National Electric Vehicles Policy* (2020) includes some incentives for manufacturers but lacks clarity, uptake incentives, and infrastructure. —SSA: The region's readiness for EVs, and electrification of end-use in general, is low and lacks adequate electricity infrastructure and financial constraints. South Africa supplemented earlier roadmaps with the *Electric Vehicle White Paper* (2023) and increased its biofuel blending mandates. Nigeria's *Long-Term Emission Development Strategy* 2060 (2024) aims for 55% EVs and 45% ethanol vehicles by 2060. Regional initiatives underway to promote EV deployment include reduced or abolished import tariffs (Ethiopia, Ghana, Mauritius, Rwanda, Seychelles); targets for EV uptake (Ethiopia, Namibia); and, reducing electricity charges on EVs and free-of-cost land for charging stations (Rwanda). Overall, though, there is a lack of well-defined policies and incentive schemes (Gicha et al., 2024).
Manufacturing	—IND: The scarce policy/support for industrial decarbonization focuses primarily on 'low-hanging fruit' such as fuel-switching to renewable energy and energy-efficiency targets. The *Perform, Achieve, Trade* (PAT) scheme mandates energy-efficiency targets and excess saved energy being tradable via energy saving certificates. RPOs in manufacturing require large power consumers like steel and cement industries to procure a minimum renewable electricity percentage of total consumption. Policy is evolving to promote green hydrogen; for example, the Indian government issued pilot project guidelines with USD 128m investment for use of green hydrogen in shipping, steel manufacturing, and transport (2024). To replace conventional hydrogen demand with renewable hydrogen, industrial mandates and quota obligations are being considered. —SSA: Energy transition and investment plans, such as in Ghana (2023) and Nigeria's *Long-Term Emission Development Strategy* (2023), reflect investment requirements instead of existing domestic policy. South Africa's *Industrial Policy Action Plan* (IPAP), reviewed in 2024, works in combination with some tax incentives to support activities with potential for decarbonization. Overall, decarbonization options (process, efficiency, and fuel and feedstock switching), as suggested by the National Business Initiative (2023), are hampered by lack of carbon pricing. Access to renewable power and green hydrogen at scale is an issue. Another uncertainty lies in the future feasibility of CCUS, for which there are no relevant policy/regulatory frameworks. High-income regions' climate policies and translation into trade relations, such as through carbon border adjustment mechanisms, will impact SSA.
Buildings	—IND: India's amendment of its *Energy Conservation Bill* advances efficiency measures. Pakistan developed the *Energy Conservation Building Code* (ECBC 2023) with support from the German Development Cooperation to set standards for energy-efficient design in residential buildings. —SSA: There are minimum energy performance standards for space cooling in Kenya, Nigeria, Rwanda, and South Africa, and growing implementation of national standards and support for energy efficiency in buildings in Kenya, South Africa, and Tanzania, with some disjointed policy in Nigeria.

How will carbon prices develop?

Carbon pricing is the main market-based instrument in the policy toolbox to reduce CO_2 emissions. It provides financial incentives for reducing emissions by assigning to polluters part or all of the cost of emissions, and can be implemented either through a tax on carbon emissions or via an emissions trading system (ETS). The potential of carbon pricing remains largely unrealized despite its crucial role in accelerating climate change mitigation and de-risking low-carbon investment. Carbon pricing must increase in both coverage and price level to drive transformational change to meet the *Paris Agreement* goals.

Carbon pricing systems take time to mature; it has taken around 20 years to reach European ETS-1 levels. For that system to be emulated in other regions, carbon pricing schemes must become increasingly stringent over time in limiting the overall volume of emissions, expanding sector coverage, and phasing out exemptions. Carbon pricing alone is typically insufficient to drive decarbonization and should thus be implemented alongside other measures. Despite some momentum for carbon pricing around the world, we do not expect any other region to reach the carbon price levels of Europe by 2050.

We derive a best estimate of the trends and future price levels in existing and future expected schemes for use in our analysis (Figure 6.3). To reflect the scheduled 2027 start of the EU ETS-2 (buildings and road transport sectors), which aims to bring 75% of EU emissions under a carbon pricing scheme to complement other policies, we incorporate the trajectory seen in Table 6.5 which influences fuel selection in the forecast. We expect price levels to be moderate given the struggle to balance affordability, emissions reduction, and possible backlash from citizens more directly affected by the ETS-2 pricing imposed on fuel suppliers.

Our estimate is based on research including engagement with experts in academia and business, recent policy developments, and a review of status reports from leading organizations. Highlights from global expert reports including the International Carbon Action Partnership (ICAP, 2024) and the World Bank (WB, 2024) are:

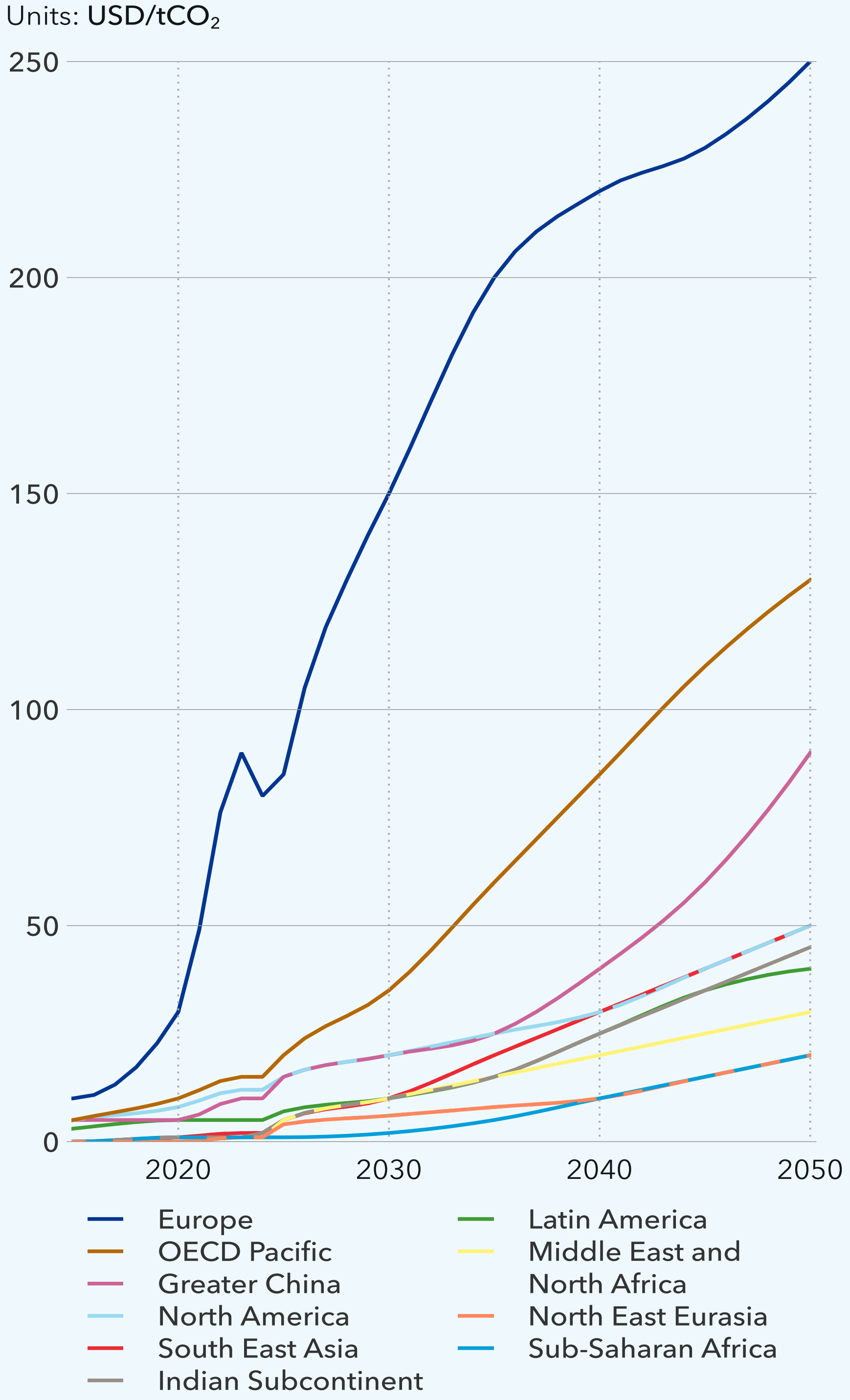
- Around 24% of global emissions are covered by carbon pricing policies (taxes and ETS).
- 75 carbon pricing instruments have been implemented worldwide, up from 73 in 2023.
- Around 70% of jurisdictions with carbon pricing have implemented multiple instruments.
- Carbon pricing instruments led to record high revenues of USD 104bn in 2023.
- Almost 40% of carbon revenue was earmarked for green spending and 10% was used to compensate households and businesses disproportionately affected by carbon pricing in 2022.
- Commencement of the EU Carbon Border Adjustment Mechanism (CBAM) affects emissions reporting for production worldwide.

> Carbon pricing must increase in both coverage and price level to drive transformational change to meet the *Paris Agreement* goals.

TABLE 6.5
European ETS-2 trajectory

	2027	2028	2029	2030	2035	2040	2045	2050
USD/tCO_2	50	50	50	50	60	100	150	200

FIGURE 6.3
Carbon price by region



Regional carbon price (CP) highlights

- **North America (NAM):** Canada has a federal, economy-wide CP policy with consistent price increases. In the US, CP policy is decided at state level, not federal. 12 US states (accounting for a third of the US GDP) participate in CP schemes (C2ES, 2024), with variation in coverage and free allocations. We do not expect CP to expand to more states. The regional average carbon price level is USD 20/tCO_2 (2030), USD 30/tCO_2 (2040), and USD 50/tCO_2 (2050). The effective CP on industrial emissions is about 50% lower.

- **Latin America (LAM):** Several economies are working on ETS development, with earliest implementation by 2030. Argentina, Chile, and Colombia support 2050 net-zero targets. Some countries have carbon taxes at low levels, except Uruguay with a tax rate at USD 167/tCO_2 (2024). The regional average carbon price level is USD 10/tCO_2 (2030), USD 25/tCO_2 (2040), and USD 40/tCO_2 (2050).

- **Europe (EUR):** Europe is a pioneer region in CP, which is key to funding the green transition. There is a higher burden on EU ETS-1 sectors (62% emissions reduction target by 2030) and ongoing decarbonization of power, extension of the ETS-1 to include maritime, full auctioning from 2026 onwards for aviation, and gradual phase out of free allowances to CBAM sectors (from 2026 to 2034). This indicates that hard-to-abate transport and industry abatement measures will increasingly be price-setting. There was a temporary easing of supply allowances, but they will tighten again after 2026. Several countries have announced or implemented carbon taxes: for example, the UK's domestic tax (December 2023) will take effect from 2027. The regional average carbon price level is USD 150/tCO_2 (2030), USD 220/tCO_2 (2040), and USD 250/tCO_2 (2050).

- **Middle East and North Africa (MEA):** There are net-zero goals from 2050 to 2060 and focus on climate action after hosting COP27 in Egypt and COP28 in UAE. However, several countries have a high level of fossil-fuel subsidies (IEA, 2023b). KSA will launch carbon credit exchange and Turkey will pilot ETS in 2024. There is a slow shift toward investment in low-carbon options as part of diversifying economies. The regional average carbon price level is USD 10/tCO_2 (2030), USD 20/tCO_2 (2040), and USD 30/tCO_2 (2050).

- **North East Eurasia (NEE):** There is slow CP adoption across the region. Existing schemes (Kazakhstan, Ukraine) remain at low price levels. CP pressure is reduced on Russia, the region's largest economy, as it shifts trade away from Europe. CP in Ukraine will strengthen if it joins the EU. The regional average carbon price level is USD 6/tCO_2 (2030), USD 10/tCO_2 (2040), and USD 20/tCO_2 (2050).

- **Sub-Saharan Africa (SSA):** Like the Indian Subcontinent, priorities are development and energy access. We expect domestic CP schemes from 2035 onwards. South Africa plans to increase its carbon tax to 2050. Nigeria has announced ETS, but it lacks clarity and concrete implementation plans. The regional average carbon price level is USD 2/tCO_2 (2030), USD 10/tCO_2 (2040), and USD 20/tCO_2 (2050).

- **Greater China (CHN):** Developing the carbon footprint management system and expanding the coverage of the national ETS to more sectors are key tasks listed in China's 2024 *Work of the Government report* (MEE, 2024). The EU's *CBAM* is a driver of the sequence of ETS inclusion of industries. After emissions peak during the *15th FYP* period to 2030, policy will shift to 'dual carbon control' and set an absolute emissions cap and carbon intensity (State Council, 2024). Auctioning allowances is expected by the early to mid-2030s. Industry abatement measures will increasingly be price-setting as power decarbonizes, suggesting a surge after 2040 to achieve carbon-neutrality by 2060. The regional average carbon price level is USD 20/tCO_2 (2030), USD 40/tCO_2 (2040), and USD 90/tCO_2 (2050).

- **Indian Subcontinent (IND):** India has set a net-zero goal for 2070 and has plans for a domestic carbon market (CCTS) to cover energy-intensive industrial sectors. The scheme will be based on energy efficiency rather than an absolute cap and the compliance carbon market is planned for 2026. As of 2024, entities from India can voluntarily participate in international crediting programmes. Pakistan is considering an ETS scheme but has made no concrete developments. The regional average carbon price level is USD 10/tCO_2 (2030), USD 25/tCO_2 (2040), and USD 45/tCO_2 (2050).

- **South East Asia (SEA):** There are net-zero announcements and some CP schemes. Indonesia launched a carbon exchange platform in 2023 that aims to transition to a hybrid cap-tax-and-trade system by 2025. Thailand is developing a voluntary ETS, launched a carbon credit trading platform, and is expected to introduce a carbon tax in 2024 or 2025. Vietnam plans to launch a trading platform in 2025, a pilot ETS in 2027, and to achieve full implementation by 2030. Malaysia has voluntary ETS plans, and Singapore's carbon tax rate will be increased gradually to 2030. The regional average carbon price level is USD 10/tCO_2 (2030), USD 30/tCO_2 (2040), and USD 50/tCO_2 (2050).

- **OECD Pacific (OPA):** CP plays an important role in the net-zero policy mix in OPA. It trails Europe, but we expect OPA will follow a similar trajectory. Japan has local schemes and plans to introduce a mandatory national ETS (GX-ETS) from 2026. This will be complemented by a carbon levy on fossil-fuel importers from 2028. Other national schemes have varying emissions coverage: 73% in South Korea, 26% in Australia, and 48% in New Zealand. All countries are expected to have some CP reforms with future coverage increases. There is increasing political pressure on Japan and Australia to strengthen their CP commitments. The regional average carbon price level is USD 35/tCO_2 (2030), 85/tCO_2 (2040), and USD 130/tCO_2 (2050).

6.4 POLICY FACTORS IN THE ETO

Our forecast factors in policy measures spanning the entire policy toolbox outlined in Section 6.2. 12 policy considerations exert influence in three main areas:

a) Supporting technology development and activating markets, thus closing the profitability gap for low-carbon technologies competing with conventional technologies.

b) Applying technology requirements or standards to restrict the use of inefficient or polluting products and technologies.

c) Providing economic signals (e.g. price incentives) to reduce carbon-intensive behaviour.

The policy analysis informing our Outlook ensures detailed coverage of the largest economies that collectively represent 80% of total energy use of each Outlook region. We map policy documents for existing, enforceable policy/measures and indications of planned and future policy developments to assess their likely impact. Model-specific policy factors are thus derived based on policy mapping.

In deriving an ETO model-specific policy factor, we take the following steps:

- Consider and differentiate regional willingness/ability to implement support/subsidies.
- Translate country-level data into expected policy impacts, then weigh and aggregate to produce regional figures for inclusion in our analysis.

Next, we detail how each of the 12 policy factors are incorporated into our analysis.

1. Renewable power support

- Renewable electricity build-out is advanced by governments in all regions, increasingly through market-led approaches such as tendering processes and auctions for certain volumes of renewable power.

- Support mechanisms for renewable generation, including: 1) investment or production cost support / tax credits, and 2) Contracts-for-Difference (CFDs; two-sided or one-sided) depending on region reflecting regional auction strike prices.

- Energy security considerations are reflected by favouring domestically available energy sources (e.g. solar and wind, coal or natural gas, nuclear). We assume incentives in the range of 6% to 15% of the levelized cost of electricity, based on existing support levels provided by countries and available information on willingness to pay for energy security. The energy sources and technologies incentivized are region dependent and reflective of resource endowments and technological know-how. Incentives are provided to nuclear and variable renewable energy sources (VRES) in Europe, OECD Pacific, and Greater China. In Sub-Saharan Africa, South East Asia, and the Indian Subcontinent, incentives are provided to coal and VRES. Gas is incentivized in the Middle East and North Africa and North East Eurasia. Conversely, these countries are disincentivizing import-dependent resources.

- Carbon pricing and cost of capital increase reduce the attractiveness of fossil-based generation.

2. Energy storage support (batteries)

- Existing and planned policy support translates to an average support as a percentage of battery unit costs for battery-storage technologies.

- Support levels increase with the share of variable renewables in regional electricity generation, incentivizing investment in flexibility while reflecting regional differences in willingness/ability to implement support.

3. Zero-emission vehicle support

- Our model reflects an average regional EV support for both battery-electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs), based on existing support at the country level.

- We account for subsidies, tax exemptions, and reduced import duties and translate these into an average CAPEX support per region per vehicle type.

- We assume a slight initial growth and then a decline in preferential treatment from the current levels thereafter. The support is capped by the EV cost disadvantage.

- We map country-level targets for public fast-charging (greater than 22kW) infrastructure roll-out to identify EV uptake barriers. As charging infrastructure expands over the next decade, this is increasingly likely to be on market terms, and associated grid-infrastructure build-out will follow without constraints.

4. Hydrogen support

- On the supply-side, hydrogen infrastructure and production have projects receiving support to either CAPEX or OPEX, whichever is higher: 1) CAPEX support is estimated on the basis of total annual government funding programmes and reflected as a percentage subsidy for the capital cost of low-carbon hydrogen production routes, or 2) OPEX support, e.g. in Europe reflecting the CfDs expected from the Hydrogen Bank, and in North America reflecting the US's tax credit 45V and Canada's investment tax credit to green hydrogen. The full subsidy remains until 2030 and is gradually halved to 2050 unless specific end-data is available. We reflect emission intensity requirements for electrolysis-based hydrogen production that rely on grid-based electricity set out in the US and EUR. We assume that the hydrogen producers in the respective regions, in order to get maximum support, will pay a cost premium to source renewable electricity (e.g. RES-E PPA documentation), with the premium gradually declining as the grid's emission intensity declines. In addition, our model is consistent with additionality (renewable electricity powering hydrogen production must come from new capacity that would not exist in the absence of hydrogen/RFNBO production) and temporal matching (future hourly matching of renewable electricity and hydrogen production) requirements for grid-based electrolysis.

  The support on the supply-side has spill-over effects for hydrogen demand in end-uses through reductions in hydrogen price.

- For the demand-side, a hydrogen-policy factor reflects CAPEX support to manufacturing and buildings but varies by region in terms of policy focus and percentage level of CAPEX, according to government funding programmes. The full subsidy remains until 2030 and is then gradually halved to 2050.

- For road transport/vehicles, the speed of hydrogen uptake is determined by a hydrogen-policy factor reflecting, among other parameters, FCEV CAPEX support including refuelling infrastructure. Examples include incentives driven by municipality-based CAPEX reduction policies for hydrogen-fuelled public buses.

- For shipping and aviation, fuel-mix shifts are driven by fuel-blending mandates and carbon pricing, as well as consumer push in certain segments like vehicle transport.

- CCS in low-carbon hydrogen production is mainly driven by regional carbon prices. The main trigger for CCS uptake will occur when carbon prices are higher than the cost of CCS. In addition, regional policies that provide specific support for CCS will enable the initial uptake and reduce costs. This policy support will be reduced when carbon prices become high enough to sustain growth. For the North America region, blue hydrogen is supported via either the 45Q tax credit (see CCS below) or the 45V; we assume a common level for either of the two tax credits, given that qualifying projects apply for whichever tax credit yields the highest support level.

5. Carbon capture and storage & direct air capture support

- Historical CCS implementations, and the future project pipeline of capture and storage capacity is fully incorporated through 2030, as reported by the Global CCS Institute (2023). These projects receive investment and operational government support.

- Regional carbon prices determine the uptake of CCS in power, manufacturing, and industrial processing.

- Regional policy support for CCS beyond the carbon price is integrated based on the gap between regular CCS costs and carbon price. The support is intended to close this gap and enable initial CCS uptake. Projects receive support reflecting government funding programmes as a percentage subsidy for the capital cost. Projects in the US benefit from the 45Q tax credit, which also distinguishes between capture-storage and capture-utilization. Policy support is reduced when the gap between carbon price and CCS costs is narrowed.

- Direct air capture support reflects announced funding in the North America region. In the US, the IRA (2022) increased the 45Q tax credit to USD 180/tCO_2 captured for storage via DAC. We have implemented this in our model as subsidies in the region.
  A much lower level of subsidies (one sixth of that) is also assumed for Europe to reflect the European Commission’s target to store up to 50 $MtCO_2$ a year by 2030, including from DAC, as well as the UK's 2023 announced funding of up to GBP 20bn (around USD 25bn) for CCUS applications, including for DAC.

6. Standards for energy efficiency

- Standards and regulation: We incorporate (existing and planned) for energy use and efficiency improvements in buildings, transport, and industry sectors.

- Buildings: Standards for insulation against heat loss/gain and energy use for appliances and lighting are used as guides for setting the input assumptions. However, the policy effects are not quantified explicitly. Additionally, for the North America and Europe regions, higher retrofitting rates of buildings and envelopes are based on subsidies and/or tax credits for insulation and weatherization of buildings.

- Vehicles: Efficiency and emissions standards per region are incorporated and translated into normalized test-cycle values (New European Driving Cycle, NEDC). An adjustment factor per region is applied to derive real-world fuel consumption from the theoretical NEDC values. The fuel-efficiency trajectories towards 2050 follow the trends determined by these real-world-adjusted standards, corrected for EV uptake.

- Shipping: The IMO 2050 GHG strategy (IMO, 2023) significantly strengthened its ambition levels in 2023 and now aims for net-zero emissions from ships 'at or around 2050'. The IMO regulations include specific energy efficiency requirements like the *Ship Energy Efficiency Management Plan* (SEEMP) and Energy *Efficiency Existing Ship Index* (EEXI). Since hydrogen-based or bio-based fuels are significantly more expensive than conventional fuels, the IMO strategy also indirectly pushes energy-efficiency measures as a more cost-effective way to achieve maritime decarbonization goals.

7. Bans, phase-out plans and mandates

- Bans on ICE vehicles are not incorporated in the forecast, but model results are associated with announced bans.

- Phase-out plans on nuclear power are incorporated. For coal-fired power generation, our forecast references the phase-out plans. However, due to market economics and reduced cost-competitiveness, shutdowns might happen earlier than phase-out plans suggest.

- Regional biofuel-blend mandates currently in place are considered and we foresee further strengthening of these in front-runner regions such as EUR and NAM. Mandates will likely be enhanced in the future to include other sustainable aviation fuels (SAFs).

- Region-specific pushes both from business and from individuals that are willing to pay for sustainable aviation will enable a gradual increase in uptake of uncompetitive (on cost) aviation fuels such as hydrogen and SAFs.

8. Carbon pricing schemes

- Our carbon-price trajectories (Figure 6.3) are reflected as costs for fossil fuels in manufacturing and buildings, and in power, hydrogen, ammonia, and methanol production where progressive participation in the same regional and/or sectoral carbon-pricing schemes is assumed. Some regions (CHN, EUR, NAM, OPA) are projected to reach carbon-price levels in the range of USD 20 to 150/tCO_2 by 2030 and USD 50 to 250/tCO_2 by 2050. Across all 10 regions, carbon pricing by mid-century is projected to range between USD 20/tCO_2 (NEE and SSA) and USD 250/tCO_2 (EUR). For the ETS-2 scheme in Europe, the projected trajectory is USD 50/tCO_2 by 2030 increasing to USD 200/tCO_2 by 2050 (Table 6.5).

- Carbon-price exemptions: We have reflected carbon-price exemptions available to many industries and lack of carbon prices in jurisdictions inside our regions. For Europe, we assume exemptions to be removed by 2034 in line with EU CBAM policy. For North America, manufacturing sector carbon prices apply roughly to 50% industries on average throughout our forecast horizon.

TAX

9. Taxation of fuel, energy, carbon and grid connections

- Fossil fuels used in road transport are taxed at the consumer level, labelled as fuel or carbon taxes.

- Effective fossil-carbon rates are incorporated in fuel prices for road transport, with taxation highest in Europe, and the rate increasing in regions with taxation. North East Eurasia, South East Asia, and the Middle East and North Africa have fossil-fuel subsidies.

- We assume that these taxes will increase in line with a region’s carbon-price regime, rising at a quarter of the carbon-price growth rate.

- Energy tax rates incorporated for other demand sectors (buildings, manufacturing) encourage switching from fossil fuels to electricity and hydrogen. In order to support hydrogen uptake, we expect hydrogen in industry to be exempt from VAT in all regions.

- Taxes and grid tariffs for grid-connected electrolysers are assumed to be a 10% surcharge over the wholesale electricity price.

- Taxes on electricity for transport are calculated from the share of charging types and their prices compared with the residential price, and applied in regions, except those with negative taxation on fuel use (i.e. fossil-fuel subsidies).

10. Air pollution intervention

- Policy interventions are reflected by an air-pollution cost proxy that transfers costs of control measures to an operating cost per kWh, incorporated in power and manufacturing sectors.

- A regionally dependent ramp-up rate is used, going from 0% to 100% implementation of the operating cost over a certain period, indicating that more and more regulations will be enforced on pollutants and plants.

11. Plastic pollution intervention

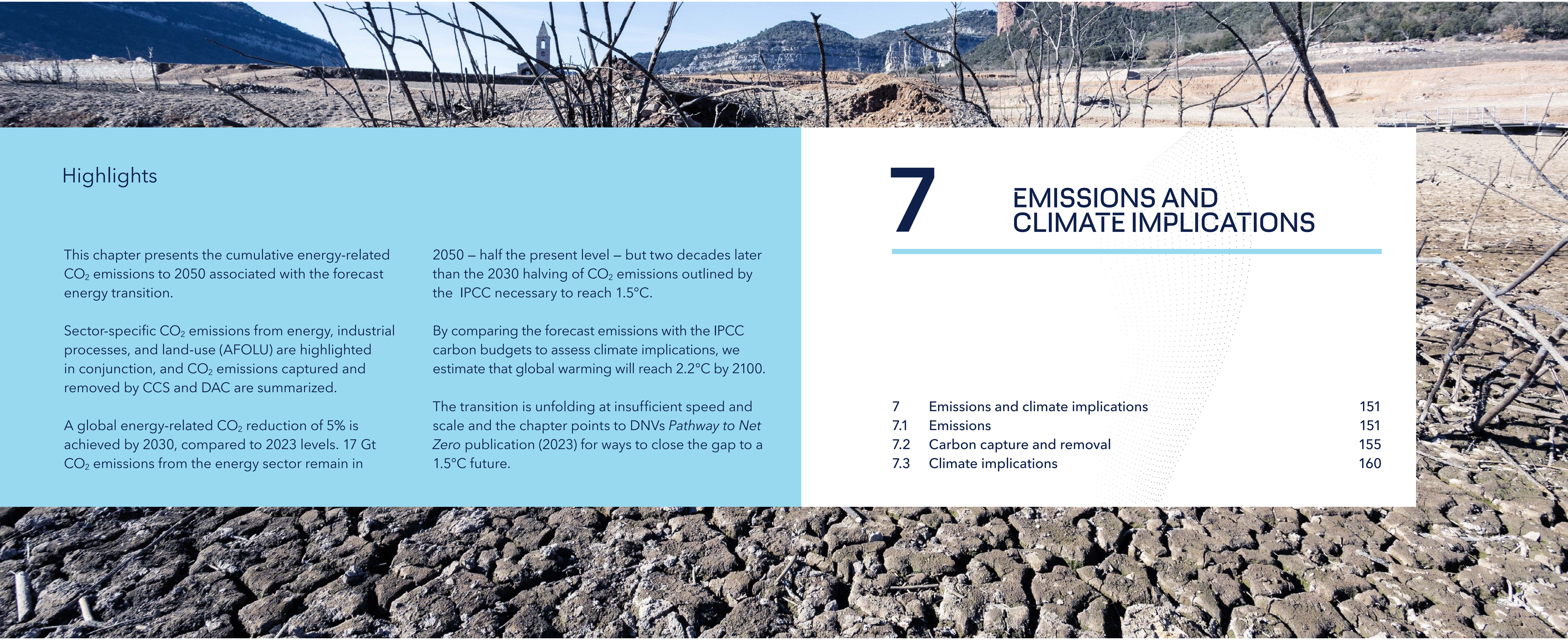
- Policy interventions on plastics – such as mandated recycling, taxes on unrecycled plastic, trade restrictions, and extended producer responsibilities – are incorporated in the form of recycling rates and an effect of reduction and substitution on demand.

- The projected recycling rates (mechanical and chemical) and the effect of reduction and substitution builds on the *Reshaping Plastics* report for Plastics Europe (Systemiq, 2022), assume that the most-likely future policy interventions correspond to those in the Circularity scenario (a combination of the 'recycling' and 'reduction & substitution' scenarios). Among the regions, EUR is expected to be a front-runner and the other ETO regions are assumed to follow with delays ranging from 5 to 15 years.

CH_4

12. Methane intervention

- Methane intervention and abatement, such as those resulting from the *Global Methane Pledge* (launched at COP26, 2021, promising at least 30% reduction from 2020 levels by 2030) are incorporated. Partial energy-sector reductions are achieved as a result of carbon prices deployed against methane abatement technologies and their marginal costs. Additionally, in North America, increased methane fees induce greater methane abatement.



7

EMISSIONS AND CLIMATE IMPLICATIONS

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Highlights

This chapter presents the cumulative energy-related CO_2 emissions to 2050 associated with the forecast energy transition.

Sector-specific CO_2 emissions from energy, industrial processes, and land-use (AFOLU) are highlighted in conjunction, and CO_2 emissions captured and removed by CCS and DAC are summarized.

A global energy-related CO_2 reduction of 5% is achieved by 2030, compared to 2023 levels. 17 Gt CO_2 emissions from the energy sector remain in 2050 – half the present level – but two decades later than the 2030 halving of CO_2 emissions outlined by the IPCC necessary to reach 1.5°C.

By comparing the forecast emissions with the IPCC carbon budgets to assess climate implications, we estimate that global warming will reach 2.2°C by 2100.

The transition is unfolding at insufficient speed and scale and the chapter points to DNVs *Pathway to Net Zero* publication (2023) for ways to close the gap to a 1.5°C future.

7 EMISSIONS AND CLIMATE IMPLICATIONS

In 2023, emissions from the energy system rose to levels above those observed at the pre-pandemic peak. We expect this upward trend to reverse in a matter of months, such that from 2025, energy-related emissions will decline steadily towards 2050. In this chapter, we show how energy-related emissions will nearly halve by mid-century, driven by significant growth in renewable energy and advances in CO_2 capture and removal. We also assess the climate impact of these emissions. Despite the decline in emissions, our analysis indicates a world heading for 2.2°C global warming by 2100, far above the targets from the *Paris Agreement*.

Over 70% of annual GHG emissions from human activities come from the energy sector, primarily from burning fossil fuels. While CO_2 is the main contributor, methane (CH_4) also plays a significant role, particularly in future climate impact projections.

In this chapter, we calculate global CO_2 emissions from the energy sector up to 2050 based on our ETO forecast. However, to arrive at a global warming estimate (i.e. the difference between global temperature at the end of this century and the pre-industrial mean), we need an estimate of total cumulative CO_2 emissions through the whole of this century. That requires additional information, and we therefore extrapolate the remaining energy-related emissions after 2050 and combine that with estimates of non-energy-related CO_2 emissions (e.g. from industrial processes and land use).

Our assessment focuses on the average surface temperature increase compared with pre-industrial levels correlated with cumulative CO_2 emissions and does not address specific climate impact effects such as flooding, drought, or forest fires.

> Despite the decline in emissions, our analysis indicates a world heading for 2.2°C global warming by 2100, far above the targets from the *Paris Agreement*.

7.1 EMISSIONS

Emissions from energy-related activities have increased alongside population growth and GDP. However, this pattern broke when emissions plateaued in 2014 following changing patterns of energy use in China and OECD countries. Emissions remained flat for several years, but began rising again in 2018. The COVID-19 pandemic caused a significant, unprecedented drop of approximately 7% in energy-related CO_2 emissions in 2020. However, energy use and emissions rebounded rapidly as economic activity resumed. The post-pandemic recovery in emissions was faster than expected, returning to 2019 peak levels by 2022. Russia's invasion of Ukraine has further disrupted the energy transition, causing an additional increase in emissions as countries prioritize energy security over decarbonization. This shift has led to increased coal use and, aided by price-capped or discounted Russian oil exports, temporarily extended oil-based electricity generation.

In 2023, global energy-related CO_2 emissions rose to 34.2 Gt. We expect these emissions to peak at 34.8 $GtCO_2$ in 2024 and then gradually decline to 32.5 $GtCO_2$ by 2030, slightly less than pre-COVID-19 levels in 2019 and 5% less compared to 2023. By mid-century, we project energy-related emissions to be 17.4 $GtCO_2$/yr, 49% less than in 2023. Coal is the largest contributor (42%) to today's energy-related CO_2 emissions, followed by oil (32%), and natural gas (25%) (Figure 7.1). We expect CO_2 emissions from coal to decline the most, decreasing by 70% between 2023 and 2050. Emissions from oil will decline by 43%, while those from natural gas will grow until 2027 before dropping to 22% less than current levels by 2050.

Sector emissions

The power sector is currently the largest contributor to energy-related CO_2 emissions, accounting for 13.8 Gt in 2023, or 40% of all energy-related emissions that year. The transport sector contributed 26% (8.9 $GtCO_2$), while manufacturing, the third main energy demand sector, accounted for 19% (6.4 $GtCO_2$). The remaining emissions came from buildings and the energy sector's own use.

By 2050, transport will be the largest emitter (29%), but it will have reduced annual CO_2 emissions of 5.1 $GtCO_2$. The power sector's energy-related emissions will be second largest (25%), but its absolute emissions will decrease to 4.4 $GtCO_2$/yr. Manufacturing's emissions will decline to 4.2 $GtCO_2$ (24%) (Figure 7.2). The factors behind these emission reductions are summarized as follows:

- **Power:** The power sector will undergo the fastest decarbonization by 2050. Most new capacity will come from solar and wind energy. Combined with the retirement of fossil-fuel power plants and the expansion of nuclear energy, this will significantly reduce emissions. In some regions, fossil-fuel plants will be equipped with carbon capture and storage (CCS), contributing to a 71% reduction in total power sector emissions between today and 2050.
- **Transport:** Emissions saw a sharp decline in 2020 due to COVID-19. Transport emissions have subsequently returned to pre-pandemic levels, and will only decline significantly in the 2030s once the growth momentum in EV uptake nullifies emissions from growth in transport services. There will be limited emission reductions in shipping and aviation. In the long term, the electrification of road transport, along with the eventual switch to low-carbon fuels in parts of maritime and aviation, will result in a 42% decline in emissions by 2050. Growth in EV uptake will further drive a rise in electricity demand which will increasingly come from renewable sources, contributing to upstream decarbonization in the power sector.

FIGURE 7.1

World energy-related CO_2 emissions by fuel source

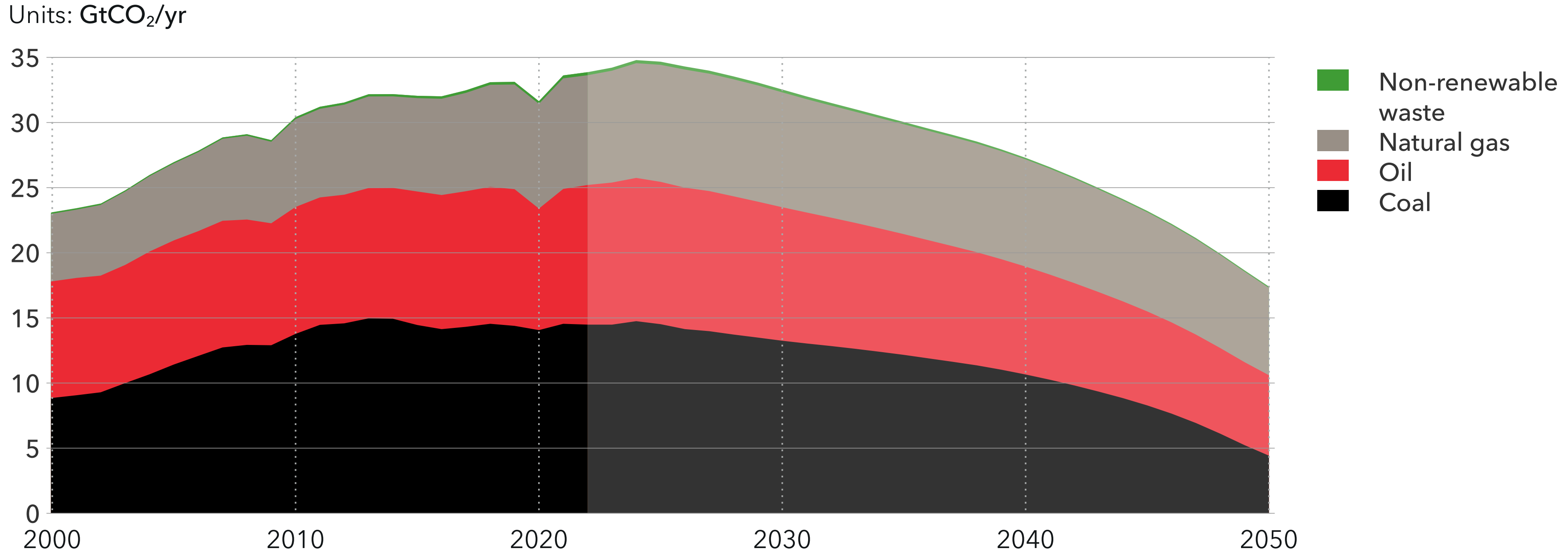
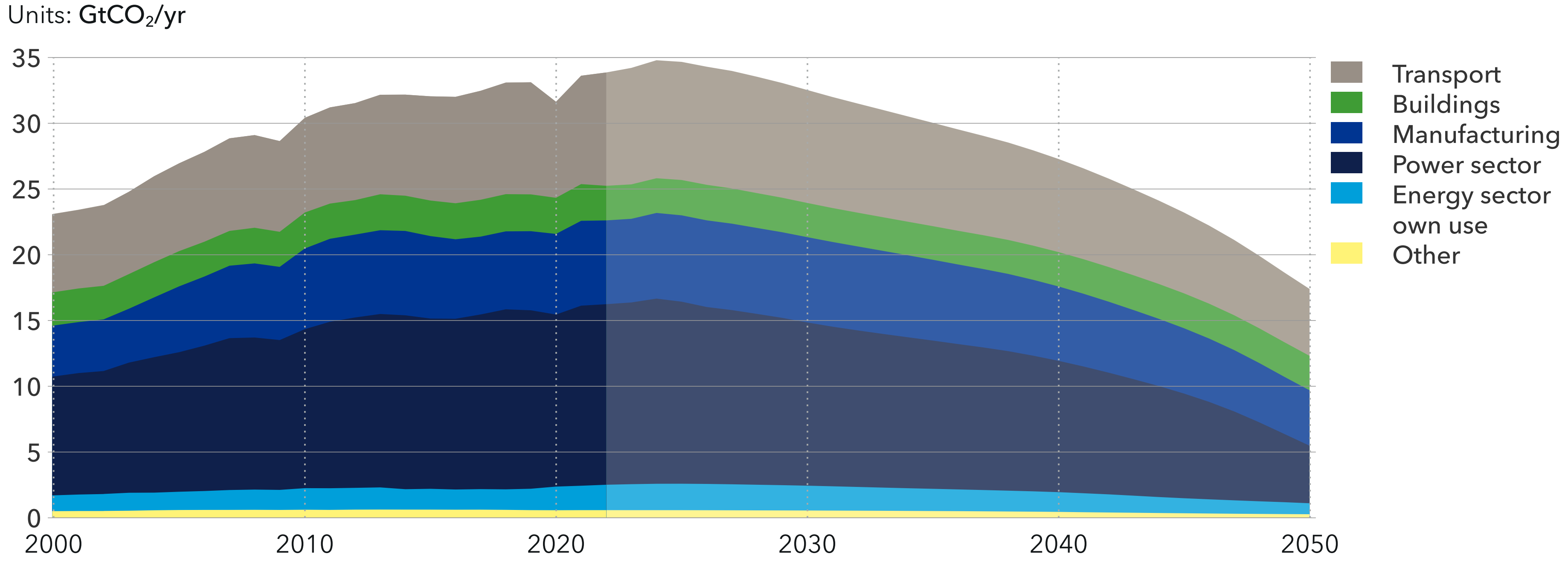


FIGURE 7.2

World energy-related CO_2 emissions by sector



Emissions from hydrogen production is allocated to own-use sector.

- **Manufacturing:** Energy-related emissions in this sector will steadily decline through electrification, fuel-switching, and CCS, and will be 34% lower than 2023 levels by 2050. However, replacing fossil fuels for high-heat processes will remain challenging and expensive. This is the key reason why manufacturing emissions only decline by a third.

- **Buildings:** Emissions from direct use of energy for heating will see limited decline due to significant growth in the number of commercial and residential buildings with increasing demand for cooking and heating of houses and water. There will be continuous improvements in energy efficiency and a shift to cleaner heating sources (e.g. electricity combined with heat pumps), but the net effect will be only a mere 0.1% decrease in buildings sector emissions between now and 2050. By mid-century, buildings will represent 16% of all energy-related emissions.

> By mid-century, we project energy-related emissions to be 17.4 $GtCO_2$/yr, 49% less than in 2023.

Regional emissions

Our 10 Outlook regions have different starting points and distinct emission trajectories over the forecast period. Greater China, currently the largest emitter, will reach peak emissions before 2030 and then decline, resulting in a 70% reduction by mid-century compared to 2023 levels.

Emissions from the Indian Subcontinent will grow rapidly towards 2035, plateau by the mid-2030s, and then start to decline, returning to roughly todays emission levels by 2050. Sub-Saharan Africa will see its energy-related CO_2 emissions increase 57% compared with today.

All other regions will reduce their emissions, with OECD Pacific leading the way (-81%), followed by Europe (-80%) and North America (-76%) (Figure 7.3). In 2050, North East Eurasia will have the highest emissions per capita at 5.7 tCO_2, followed by the Middle East and North Africa at 3.6 tCO_2 per capita, and then North America at 3 tCO_2 per capita (see the graphic on Energy, GDP, and Population on page 164). We cover regional energy-related emissions in more detail in Chapter 8.

Process-related emissions

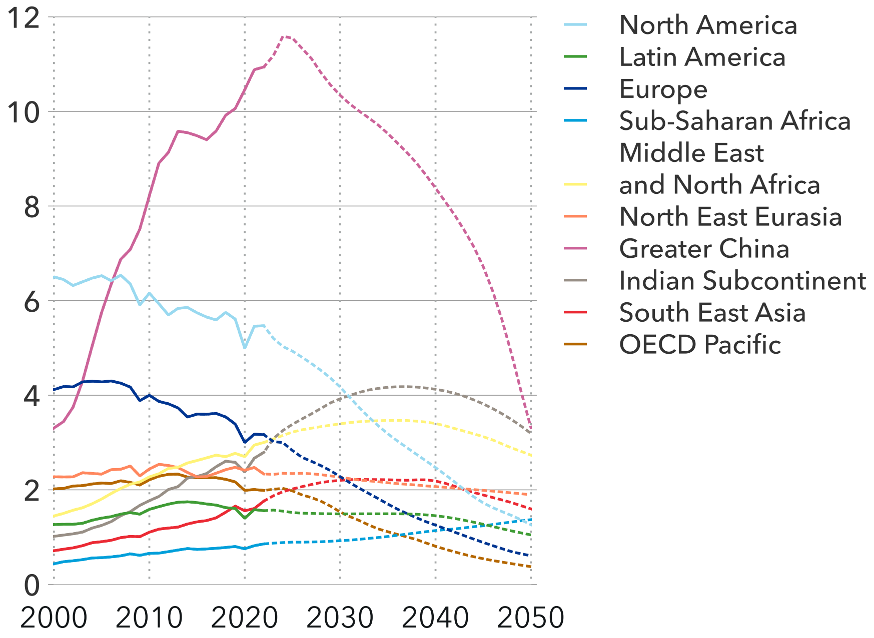
In addition to CO_2 emissions from combusting fossil fuels, a significant amount comes from industrial processes that either use fossil fuels as feedstock materials (e.g. plastics and petrochemical products) or produce CO_2 through chemical reactions (e.g. cement production). In 2023, these CO_2 emissions were 4.1 Gt, with almost half of that coming from calcination in cement production. The rest came from ammonia production, coke ovens, and the production of lime or other chemicals.

We expect a slight rise in construction and industrial activity over the next 10 years that will drive up process emissions. However, while output may stabilize at a higher level than today, improvements in production efficiency and technology, along with increased emissions capture, will lead to a decline in emissions toward 2040, with a more rapid decrease by 2050. By mid-century, process-related industrial emissions will be 11% lower than today at 3.6 $GtCO_2$/yr.

FIGURE 7.3

Energy-related CO_2 emissions by region

Units: $GtCO_2$/yr



Land-use emissions

CO_2 emissions from AFOLU are not included in our forecast and modelling of the energy transition. However, at over 4 $GtCO_2$/yr, these emissions are greater than Europe's total emissions and are significant enough to warrant inclusion when considering global CO_2 emissions and their climate implications. Accordingly, in estimating the global warming associated with our energy forecast, we take AFOLU emissions into account. Over the last 20 years, land-use emissions have grown slowly, historically averaging 5 $GtCO_2$/yr with large annual fluctuations. Recent research has adjusted land-use emissions down slightly from this historical average, with the latest estimate showing a slight decline to 4.3 $GtCO_2$/yr in 2022 (Friedlingstein et al., 2023).

There is considerable uncertainty about future changes in land use, as some countries with large forest areas are experiencing significant losses due to both non-fire-related causes and increasingly to forest fires (Weisse et al., 2024). Despite this uncertainty, we expect that climate and sustainability concerns will eventually influence policy, creating pressure to control land-use changes. Our best estimate is that annual CO_2 emissions from land-use changes will slowly decline in line with recent trend to 3.9 Gt by 2030 and then reduce at a slightly faster rate to 2.4 Gt by 2050, 45% lower than today’s levels. We will use this value when assessing the climate implications.

2100 Modelling

2050 is only 26 years away, and although the energy system of 2050 will be significantly different from today, it is also clear that in 2050 the energy system will still be in a rapid transition. We see this from all charts in this report: the energy system in 2050 is far from stable. Coal and oil will then be in steep decline and solar PV, wind, and hydrogen use will still be rising rapidly.

When looking at energy use, emissions, and the implications of emissions, it is therefore useful to look at the longer horizon and how the energy system will be changing towards 2100.

One challenge is that the uncertainty increases dramatically if we look more than a quarter century into the future, and it is questionable whether there is value in a forecast with such huge uncertainty. We believe there is.

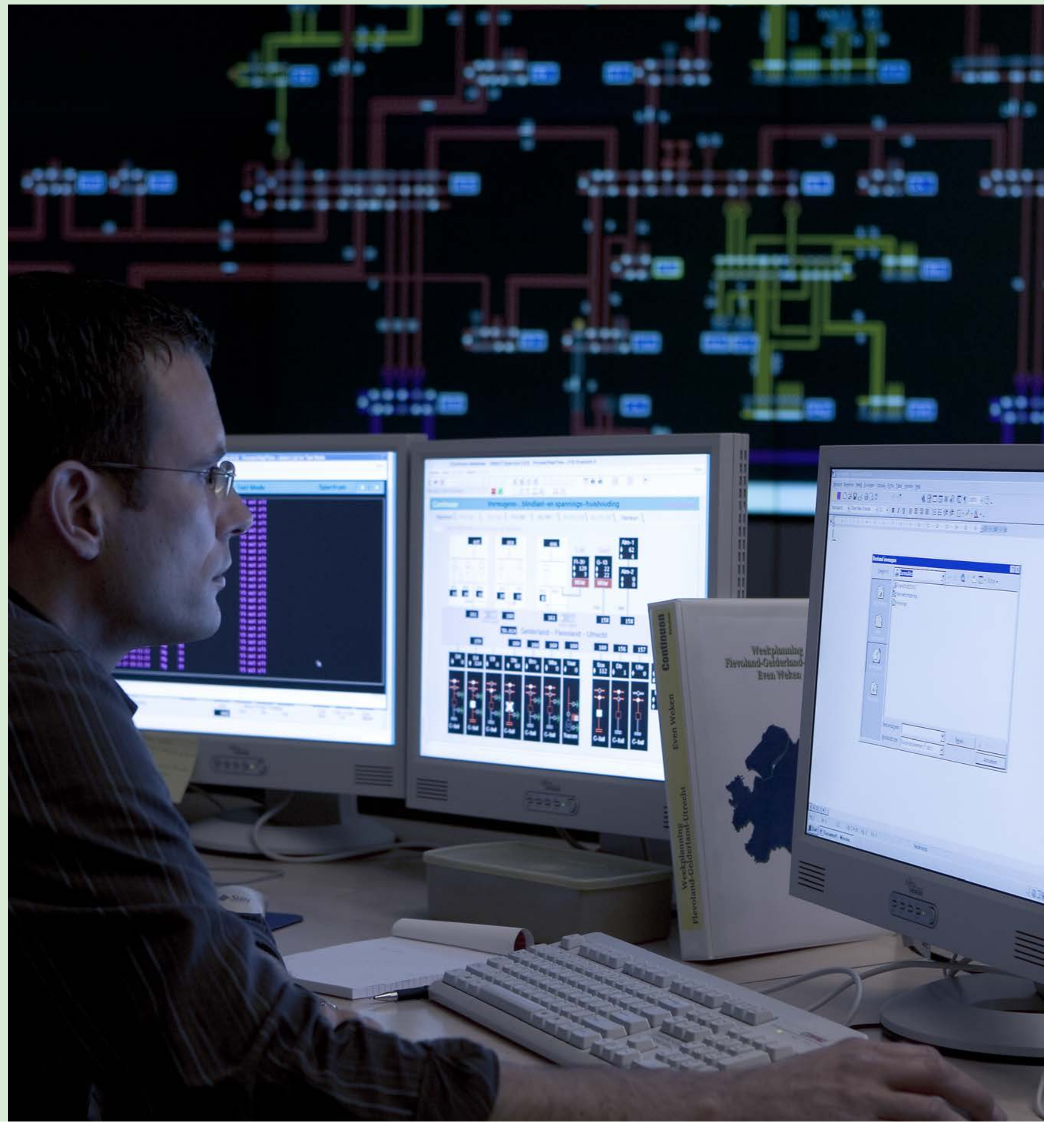
We can break the uncertainty down into five main parameters:

- **Population:** The International Institute for Applied Systems Analysis (IIASA) and UN population prospects both project peak global population in their middle-of-the-road forecasts – in 2080 and 2084, respectively. Uncertainty is perceived to be moderate; a change in the trend of declining fertility seems unlikely.
- **Economy:** Very long-term macroeconomic forecasts are associated with high degrees of uncertainty given the compounding risk that such forecasts can be systematically wrong after crises (like war) and breakthroughs (like AI) bring large shifts to long run equilibrium means and trends (Castle and Hendry, 2023). However, given that emissions will increasingly decouple from economic activity as the world decarbonizes, estimates of emissions in the second half of this century are significantly less sensitive to macroeconomic forecasts than is presently the case. Still, our assumptions regarding post-2050 GDP developments may be substantially incorrect.
- **Technology:** Technological uncertainty is moderate in the medium term. In a 75-year perspective, breakthrough technologies like nuclear fusion or superconductivity could revolutionize the energy system. Artificial Intelligence (AI), quantum computing, or other digital technologies might dramatically change our society. Although the electrification trend is certain, overall technological uncertainty is high.
- **Policy:** In the present forecast horizon to 2050, policy is the most uncertain factor in our forecast. This uncertainty persists or increases beyond mid-century towards 2100 but does not grow exponentially.
- **Behavioural change:** So far, this factor has a very modest influence on our forecast. Large changes in work and travel patterns might happen in the longer term, especially those connected to digitalization. It is likely that the ever more dramatic impact of climate change will influence attitudes and values, leading to more policy momentum for climate mitigation and adaptation.

In summary, while policy uncertainty remains, DNV finds that technological and economic uncertainties might be even more important when looking at the energy system towards 2100. These are important considerations for public and private sector stakeholders deciding on investment, regulations, and other policy priorities for the very long term. Many national climate and energy pledges and ambitions already stretch beyond 2050.

From a climate perspective, DNV's Outlook has always considered 2100, both because of the long timescales of some climate-change responses (e.g. sea level rise) and because it is a key milestone date for setting policy goals and targets to limit global warming. For example, the IPCC's *Special Report on Global Warming of 1.5°C* (2018) uses 2100 as the threshold for its 1.5°C emission pathways. In an even longer time horizon, the climate sensitivity of the planet is a key uncertainty for efforts needed to reduce the impacts of global warming.

The system dynamics methodology used in the ETO is suitable for looking into the connections and feedback between different parameters. Our ETO model itself can already run to 2100, and DNV will continue to develop the model and our perspectives for the longer time horizons, eventually presenting and discussing forecasts towards 2060, 2080, and 2100.



7.2 CARBON CAPTURE AND REMOVAL

Given the need for carbon capture and removal to ensure that the CO_2 emitted by fossil-fuel combustion does not remain in the atmosphere and contribute to global warming, we forecast 1.5 $GtCO_2$ removal per year by mid-century, compared with very little in 2023. Most (91%) of carbon removal in 2050 will be accomplished by CCS, with only 140 $MtCO_2$ (about 9%) being through direct air capture (DAC) due to its still prohibitively high costs. A quarter of CCS capacity in 2050 will be installed in fossil-fuel and bioenergy power plants.

The window is closing on humanity's ability to reduce emissions sufficiently to meet the *Paris Agreement's* aim of holding the increase in the global average temperature to well below 2°C above pre-industrial levels. We will most likely need technologies like CCS and DAC that remove CO_2 to make up the shortfall. This was a clear message in the *IPCC Synthesis Report* (2023). Even so, as we have pointed out in our *Pathway to Net Zero* report (see end of this chapter), carbon capture and removal will need to be massively extended at enormous cost – trillions of dollars invested annually – to arrive at a net zero outcome by 2050.

CCS technologies capture and remove CO_2 from concentrated streams, such as point-source emissions like manufacturing facilities and power plants. In contrast, DAC removes CO_2 in low concentrations directly from the atmosphere. In both CCS and DAC, the captured or removed CO_2 can either be transported and stored in geological or marine reservoirs or used to produce value-added products such as e-fuels. In our ETO forecast, we only consider capture and storage and have not modelled the use of captured CO_2 in production.

While CCS is a method of reducing industrial and large point-source emissions, DAC is a negative emission technology and, as such, the motivations and technologies behind the two approaches differ. Furthermore, captured bioenergy emissions are both a form of carbon capture from a concentrated source (either bioenergy power plant or industrial applications with bioenergy) and a negative emission technology (if the bioenergy is deemed to have been sourced sustainably). We denote bioenergy combustion equipped with CCS technology as bioenergy carbon capture and storage (BECCS).

> In our forecast, CCS and DAC remove less than 10% of energy-related emissions in 2050.

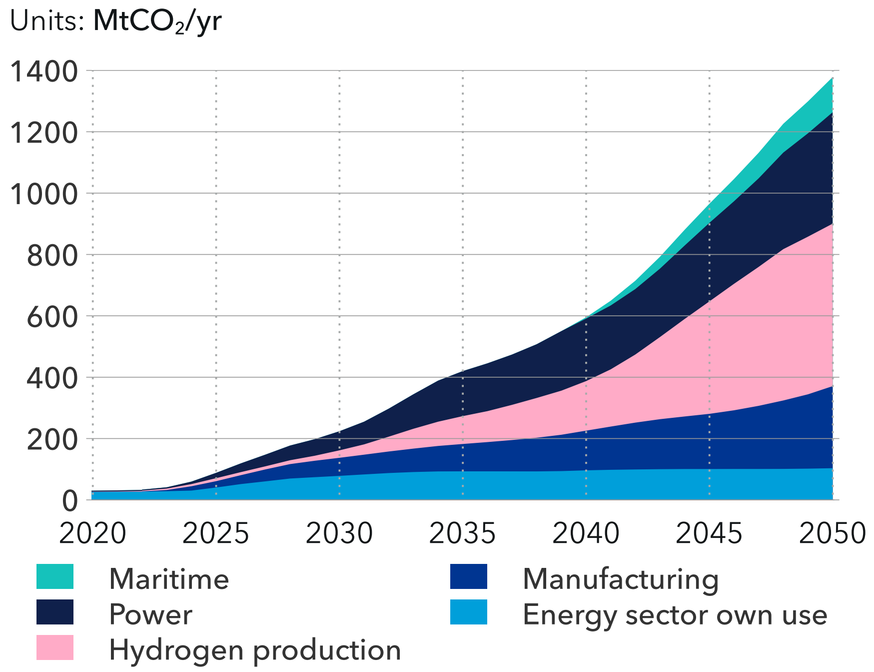
Carbon capture and storage

We forecast a dramatic transition in the CCS landscape. In 2023, total CO_2 captured with CCS was only about 43 $MtCO_2$/yr worldwide, most of it for natural gas processing and enhanced oil recovery (65%). In those cases, CCS applications are underpinned by a business case involving the use of CO_2 to extract more oil from a reservoir or the removal of CO_2 from extracted natural gas so that it may meet industry standards before being piped. Half of the current CCS facilities are in North America.

Even within the next 10 years, we see this picture changing fundamentally (Figure 7.4). In 2030, we forecast CCS to reach 225 Mt/yr, globally. A quarter of this CO_2 captured through CCS (including BECCS) will be in power generation, with examples including BECCS at Drax in Europe (Drax, 2024) and CCS at coal-fired power plants like Coal Creek (UND Today, 2023).

FIGURE 7.4

World CO_2 emissions captured by sector



Hydrogen production includes production of ammonia and e-fuels.

By 2040, there is further change in which sectors are fitted with CCS, with both hydrogen and ammonia production making deep inroads. We foresee 10% growth year-on-year in total CCS capacity from 225 Mt/yr in 2030 to 600 Mt/yr in 2040. We expect this to reach 1.4 Gt/yr by 2050. That capacity is capable of removing barely one fifteenth of energy-related emissions in the year 2050.

CCS in maritime

This year, we are forecasting onboard capture of CO_2 aboard ships in the maritime transport sector for the first time. The major uncertainty in shipping is not the technology but whether there will be a global system for receiving the CO_2 captured on board. Despite the uncertainty and the time it will take to implement, onboard capture is potentially a lower cost opportunity for shipping to mitigate some of the high costs of alternative fuels such as methanol, ammonia, and advanced biofuel. We therefore include it in our forecast from 2040 onwards. By mid-century, we foresee maritime CCS on both marine oil-based and natural gas-based ships reaching 114 Mt annually, about 8% of total captured CO_2.

CCS costs

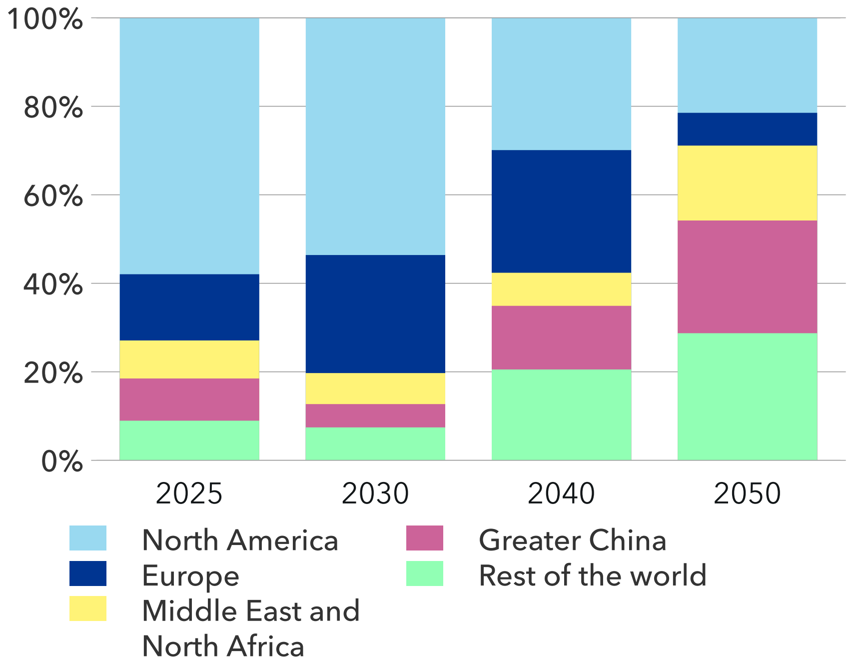
The adoption of CCS technology in different sectors is a cost-driven process in our ETO model. Two underlying mechanisms significantly impact the cost calculus: the levelized cost of CCS – i.e. the cost of CO_2 avoided by CCS – and the carbon price/cost. Emitters will need to weigh the costs of adopting CCS versus emitting the CO_2 and paying the carbon price and will favour whichever costs less.

Now and in the short term, the capital cost and the energy cost (the energy 'penalty cost') of CCS is very high. However, these costs vary across the CCS technologies in different sectors and regions. In addition, in some specific locales, support mechanisms for CCS help lower the cost calculus considerably (Sheff, 2023). These support measures include subsidies per tonne of CO_2 sequestered, state-funding for CCS transport hubs like the US's *Inflation Reduction Act* (IRA), and CCS-related infrastructure projects where states bear the cost of infrastructure and the running costs for a certain time period (e.g. the Northern Lights project in Northern Europe) (NorLights, 2024).

FIGURE 7.5

Regional split of carbon capture and storage

Units: Percentages



Given this cost logic, local support mechanisms are driving uptake of projects in the near term, while in the longer term (2030s and beyond) the assumed region-wide carbon prices will drive adoption of CCS in the different sectors and emission sources (Figure 7.4).

CCS regional developments

In 2023, the majority of CCS occurred in North America, with Europe, Greater China, and the Middle East and North Africa accounting for most of the remainder. This will be unchanged leading up to 2025 (Figure 7.5).

An increasing carbon price and persistent use of fossil fuels sees Europe's share of global CO_2 capture increase until 2040. By 2050, Europe's use of fossil fuels and bioenergy in industry (less than 40%) and power sector (less than 5%) will be quite low compared with the use of cleaner energy sources. For example, the power plants running on coal or pure methane will make up less than 5% of the total power plant fleet in 2050. The cost of running these power plants and of capturing the CO_2 is considerably higher than the carbon price in 2050. Hence, Europe's share of global CO_2 captured starts reducing from 2040 to 2050.

We expect the fossil-fuel rich region Middle East and North Africa to have an increasing share of carbon captured globally, from 5% in 2025 to about 20% by 2050. This installation of CCS on fossil-fuel production and processing systems will enable them to continue extracting fossil fuels, and in producing cleaner ammonia and hydrogen for both export and domestic use. By 2040s, most of this CO_2 capture will occur in blue hydrogen production and decarbonized ammonia production.

The region-wide carbon emission trading scheme introduced in Greater China will lead to increasing CCS in the power sector and iron and steel industry of Greater China. From accounting for a little less than 5% of the total CO_2 emissions captured globally in 2025, Greater China will have a share of 25% of global CO_2 emissions captured by 2050.

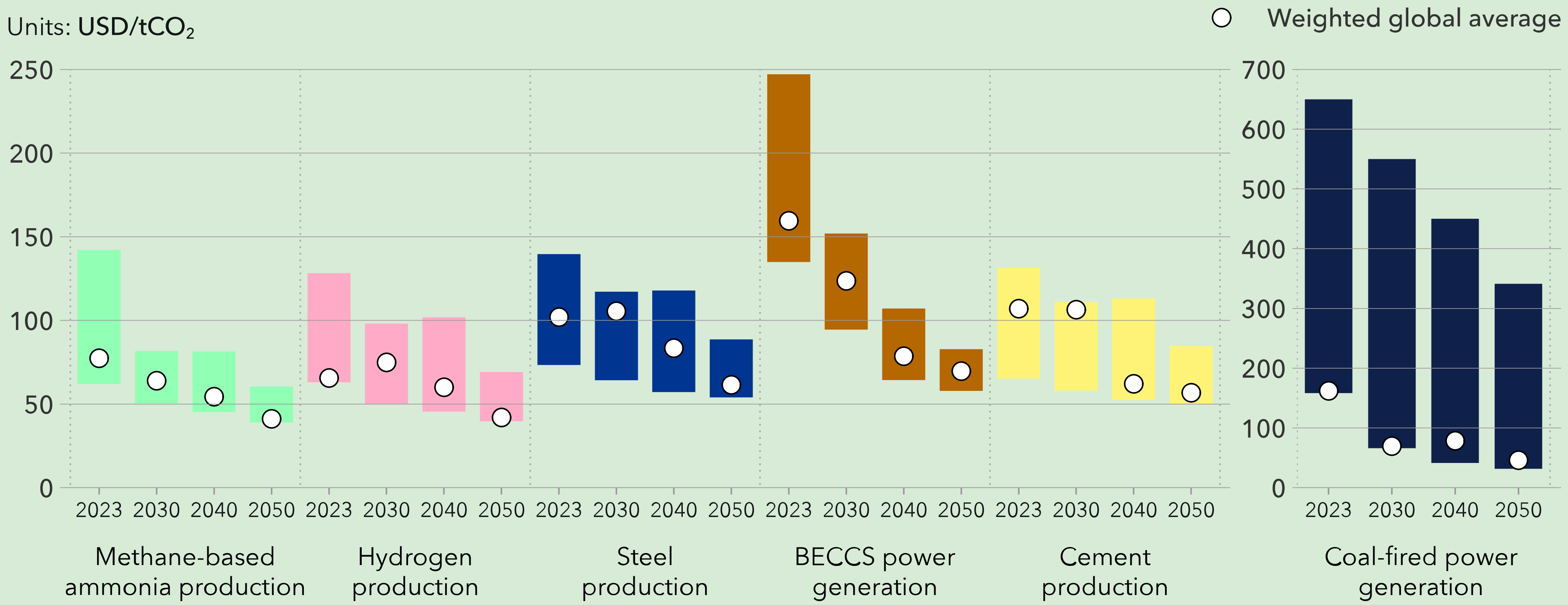
Cost of carbon dioxide avoided by CCS

Figure 7.6 shows the spread cost of CO_2 avoided of some common CCS applications and their corresponding emission-sources. Ammonia production through the Haber-Bosch process with CCS already costs less than USD 100/tCO_2 and we expect it to fall to around USD 50/tCO_2 by mid-century. We forecast similar avoided cost of CO_2 ranges for blue hydrogen as well. Both these cost trajectories will drive CCS adoption in these sectors.

Support in the years 2023 to 2030 in leading adopters and high-income regions, such as North America and Europe, drives initial CCS uptake. This leverages important cost learning that simultaneously starts reducing costs for all regions that start adopting CCS applications for these sectors.

FIGURE 7.6

Cost of installed carbon capture and storage projects for selected sectors



Direct air capture (DAC)

DAC refers to the process of removing CO_2 in low concentrations directly from the atmosphere. The CO_2 can be permanently stored in deep geological formations or used in commercial applications. This means that direct air capture plus storage (DAC+S) – also called direct air carbon capture and storage (DACCS) or carbon dioxide removal (CDR) – is a negative emission technology that can be used for offsetting emissions from other sectors, such as aviation. However, DAC is still an emerging technology that is currently prohibitively expensive to deploy at scale. Capturing and removing CO_2 in low concentrations from the atmosphere (over 100 times more dilute than in the flue gas from a gas-fired power plant) is intrinsically energy- and equipment-intensive.

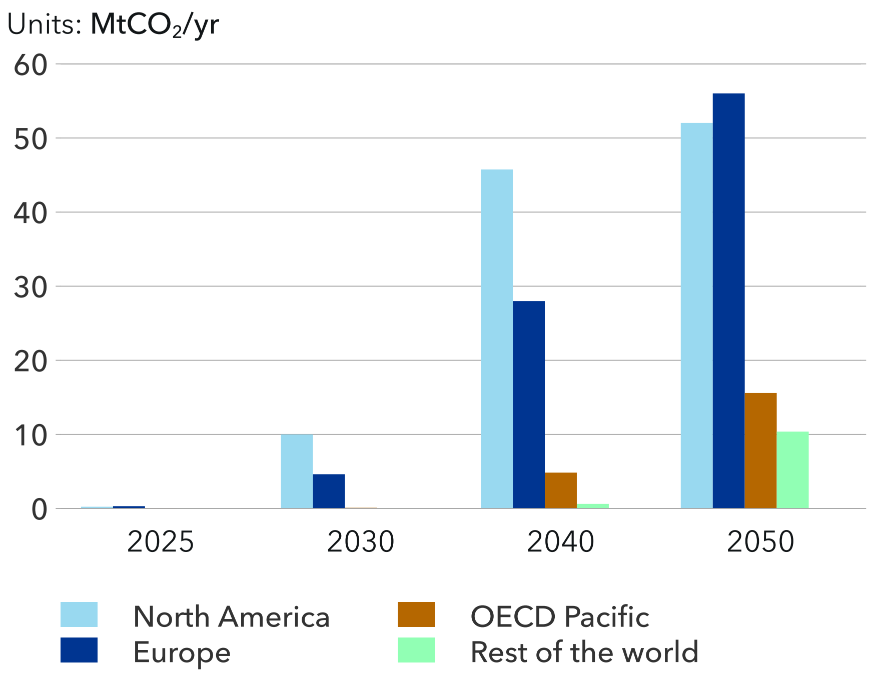
Thus, we foresee initial DAC efforts being driven mostly by voluntary and/or quasi-compliance efforts of large companies looking to offset emissions (e.g. Microsoft agreeing to pay for permanent CO_2 removal (Heirloom, 2023)) or by major players in hard-to-abate sectors like aviation as part of their compliance requirement in the future.

In our model, regions will adopt DAC based on the carbon price, the support level for DAC (e.g. the direct subsidy of USD 180/CO_2 in the US), the regional emissions from aviation, and the cost of electricity to operate the DAC plants.

Based on these factors, we foresee about 140 MtCO_2 being captured directly by a plethora of different energy-based DAC technologies by 2050, globally. This CO_2 will primarily be captured in high-income regions such as North America, Europe, and OECD Pacific, with very little coming from the other regions by mid-century. Despite this growth in DAC from very low levels today at the pilot-scale, the amounts of direct capture will be insignificant compared with our forecast emission levels. The cost-reduction trajectories for DAC technologies will not be steep enough to scale DAC levels such that it makes a significant contribution to the achievement of net-zero CO_2 emissions by 2050.

FIGURE 7.7

Direct air capture of CO_2 by region



Methane emissions

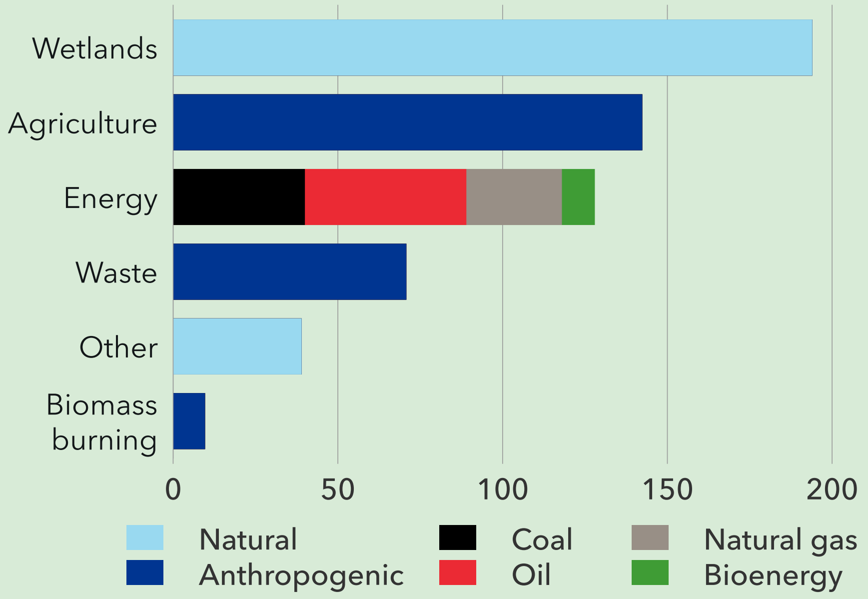
Methane (CH_4) is the second largest contributor after CO_2 to GHG-induced global warming. Nearly a third (30%) of the rise in global temperatures since the Industrial Revolution is due to doubling the concentration of CH_4 in the atmosphere. Two key characteristics determine the impact of different GHGs on the climate: how long they remain in the atmosphere and their heat-trapping ability. Methane has a much shorter half-life (12 years) than carbon dioxide (about 120 years) but is the more potent GHG. Per tonne of GHG emitted, methane is 29.8 times more potent than CO_2 over a 100-year Global Warming Potential (GWP) time horizon, and 82.5 times more potent in a 20-year GWP perspective (IPCC, 2021).

On average, 40% of annual methane emissions (about 233 Mt) come from natural sources such as wetlands (Figure 7.8). The rest (about 350 Mt) are related to human activities, with the energy sector accounting for slightly more than half of these methane missions, or 34% of the total (IEA, 2024).

FIGURE 7.8

Sources of methane emissions

Units: $MtCH_4/yr$



Adapted from IEA Global Methane Tracker (2024)

When converted to a CO_2 equivalent value using 100-year GWP, energy-related methane emissions amount to 10.4 $GtCO_2eq$, close to a third of the global CO_2 emissions from the energy sector. This is not an insignificant amount, especially given that mitigating involuntary CH_4 emissions is fiscally expedient; it may be used as energy, thus fractionally reducing the need for extraction.

According to the IEA Global Methane Tracker, large methane emission events detected by satellites rose by more than 50% from 2022 to 2023. In 2023, 118 Mt of total methane emissions were tied to fossil fuels. Major fossil fuel leaks, like the well blowout in Kazakhstan that lasted more than 200 days, were responsible for more than 5 Mt.

Around 80 Mt of methane emissions come from just 10 countries. The US is the largest emitter of methane from oil and gas operations, followed by Russia. China is by far the biggest methane emitter in the coal sector.

Global Methane Pledge

The Global Methane Pledge was launched in 2021 and as of December 2023 had been signed by 155 countries representing over 50% of total anthropogenic methane emissions. It aims to reduce global anthropogenic methane emissions by 30% by 2030 compared with 2020 levels. Despite its noble intentions, the pledge has significant shortcomings. Notably, seven major emitters – Algeria, India, Iran, Russia, Syria, Thailand, and Venezuela – are non-signatories yet account for around 30% of global methane emissions from fossil fuels.

Furthermore, fewer than a third of the 155 participating countries have detailed their reduction strategies through sector-specific targets or national action plans. For the oil and gas sector, high-level commitments could lead to a 55% reduction in emissions by 2030, but current detailed policies and regulations would only achieve around a 20% reduction, highlighting a substantial gap. For coal, high-level commitments suggest a 40% reduction by 2030, yet existing firm policies would result in less than a 10% reduction. This underscores the need for more specific measures to meet the pledged targets.

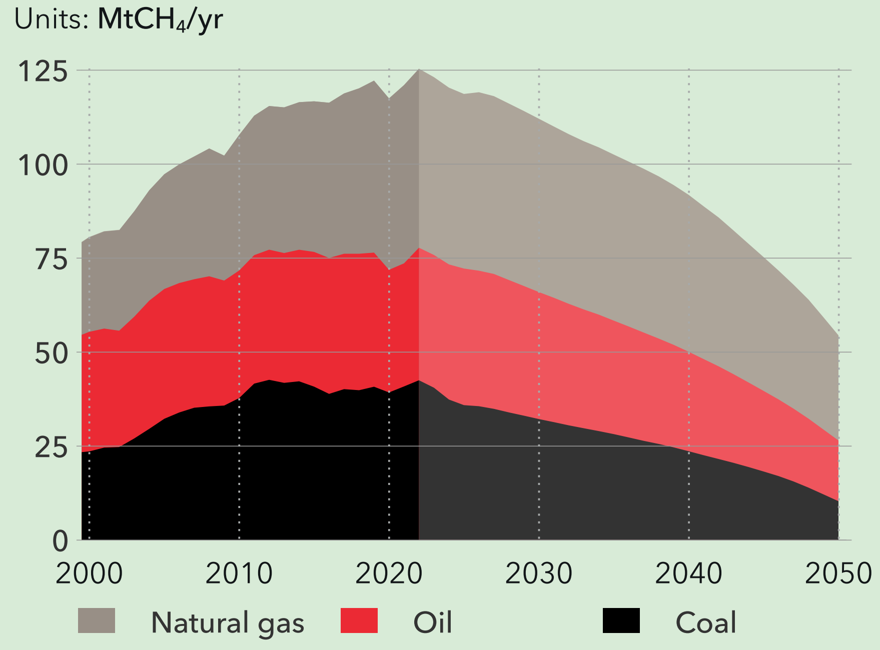
Methane emissions from fossil fuels

Our Outlook presents the methane emissions from coal mining and from oil and natural gas extraction, transmission, and distribution. We obtained historical data on methane emissions from all fossil fuels from EDGAR, the Emissions Database for Global Atmospheric Research (EC-JRC and PBL, 2021). We projected the resulting emissions based on activity levels of oil and natural gas production by field type (conventional onshore, offshore, and unconventional) and coal production. For oil and gas CH_4 emissions, we also separated the emission mechanisms, namely: vented, fugitive, and incomplete flaring.

We forecast that the world will fail to meet the *Global Methane Pledge* by 2030, at least in terms of CH_4 emissions from fossil fuels. The methane emissions from fossil fuels are 119 Mt/yr in 2030, 3% more than the 115 Mt emitted in 2020. We project 90 $MtCH_4$ emissions in 2040, 22% less than in 2020. By mid-century, CH_4 emissions will be half of what they were in 2020, primarily thanks to the reduction in demand for coal and oil.

FIGURE 7.9

World methane emissions from fossil fuels by source



Historical data source: EDGAR (2023)

In 2020, methane emissions from natural gas were 40% of total methane emissions, with coal and oil having approximately equal shares of 30% (Figure 7.9). We estimate these shares will change gradually, with coal methane emissions reducing heavily due to demand reduction. By mid-century, half the methane emissions from fossil fuels will be due to extraction, transmission, and distribution of natural gas, with oil contributing 30% and coal 20%.

Why only carbon dioxide and methane?

Other greenhouse gases, such as NO_x, HFCs, and CFCs are not considered in our report but are more potent GHGs (measured in Global Warming Potential per tonne of gas emitted) and more persistent than either carbon dioxide or methane. Two main reasons for us omitting these other gases are that the energy sector is not a significant contributor to their emission and the absolute quantities emitted are low. Thus, these emissions could potentially be much more easily reduced through regulation and are not correlated to our energy systems model.

7.3 CLIMATE IMPLICATIONS

Our forecast gives future levels of CO_2 emissions and enables us to determine the corresponding climate response and its associated temperature increase. We focus only on first-order effects and do not include possible 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

The concentration of CO_2 in the atmosphere is measured in parts per million (ppm). Pre-industrial levels were around 280 ppm (Friedlingstein, 2020) and emissions related to human activities, particularly burning fossil fuels, have resulted in a significant increase. The most recent reading in May 2024 reached another record level of 423.4 ppm (NOAA GML, 2024). Over the last 60 years, the concentration has increased by more than 100 ppm, which is of the same magnitude as the entirety of shifts observed over the previous 800,000 years (IPCC, 2021).

We forecast a continuation of CO_2 emissions linked to human activities, albeit at a decreasing rate. In contrast to methane, which on average oxidizes after approximately 10 years (IPCC, 2001), it takes hundreds to thousands of years for CO_2 to disappear naturally from the atmosphere (Archer et al., 2009). Thus, the cumulative concentration of CO_2 gives a direct indication of long-term global warming.

As there is a causal link between CO_2 concentration and long-term temperature increase (IPCC, 2021), it is possible to calculate the expected temperature increase based on the cumulative net global amount of CO_2 in the atmosphere. Similarly, limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic GHGs and pollution, gives the maximum amount of cumulative net global anthropogenic CO_2 emissions, often referred to as the global carbon budget.

The global carbon budget

The carbon budget includes several uncertainties: the accuracy of data on historical emissions, the accuracy of the estimated warming to date, the role of other GHG emissions in current warming, Earth system feedbacks, and the delay between emissions having reached net zero and the additional amount of warming inherent in the system. The closer we get to the temperature increase that we wish to avoid (e.g. increase above 1.5°C), the more these parameters contribute to uncertainty.

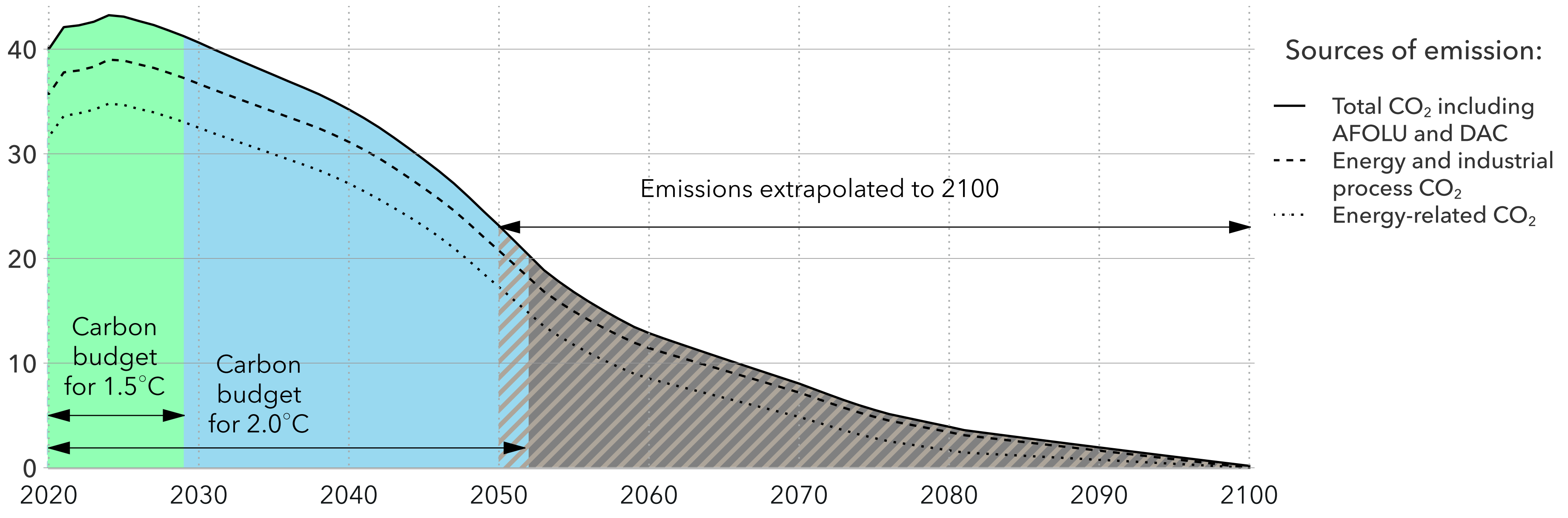
Despite these uncertainties, the carbon budget has proved to be a reasonable method to indicate potential future warming levels based on different scenarios for energy-related emissions. For our temperature estimates, we have used the 'likely' (meaning 67% probability) carbon budgets from the *IPCC Sixth Assessment Report* (IPCC, 2021). By selecting a 67% chance to stay below the selected temperature threshold, we have chosen to increase the certainty of limiting warming to our selected respective temperature thresholds. IPCC concludes that to stay below 1.5°C, we have to limit cumulative emissions from 2020 onwards to 400 $GtCO_2$ and to 1,150 $GtCO_2$ to remain below 2.0°C.

The IPCC carbon budgets have taken account of emissions from other GHGs. Methane emissions from fossil fuels or changes in agricultural practices, including fertilizer use or aerosol emissions, can have considerable influence on the size of the carbon budget. We use the IPCC scenarios in line with 'very low' and 'low' non-CO_2 emissions estimates, which follow a similar path as our CO_2 emission trajectory. If emissions from non-CO_2 GHGs are larger, then the carbon budget will be smaller and associated temperature increase larger.

FIGURE 7.10

World CO_2 emissions and associated carbon budgets

Units: $GtCO_2$/yr



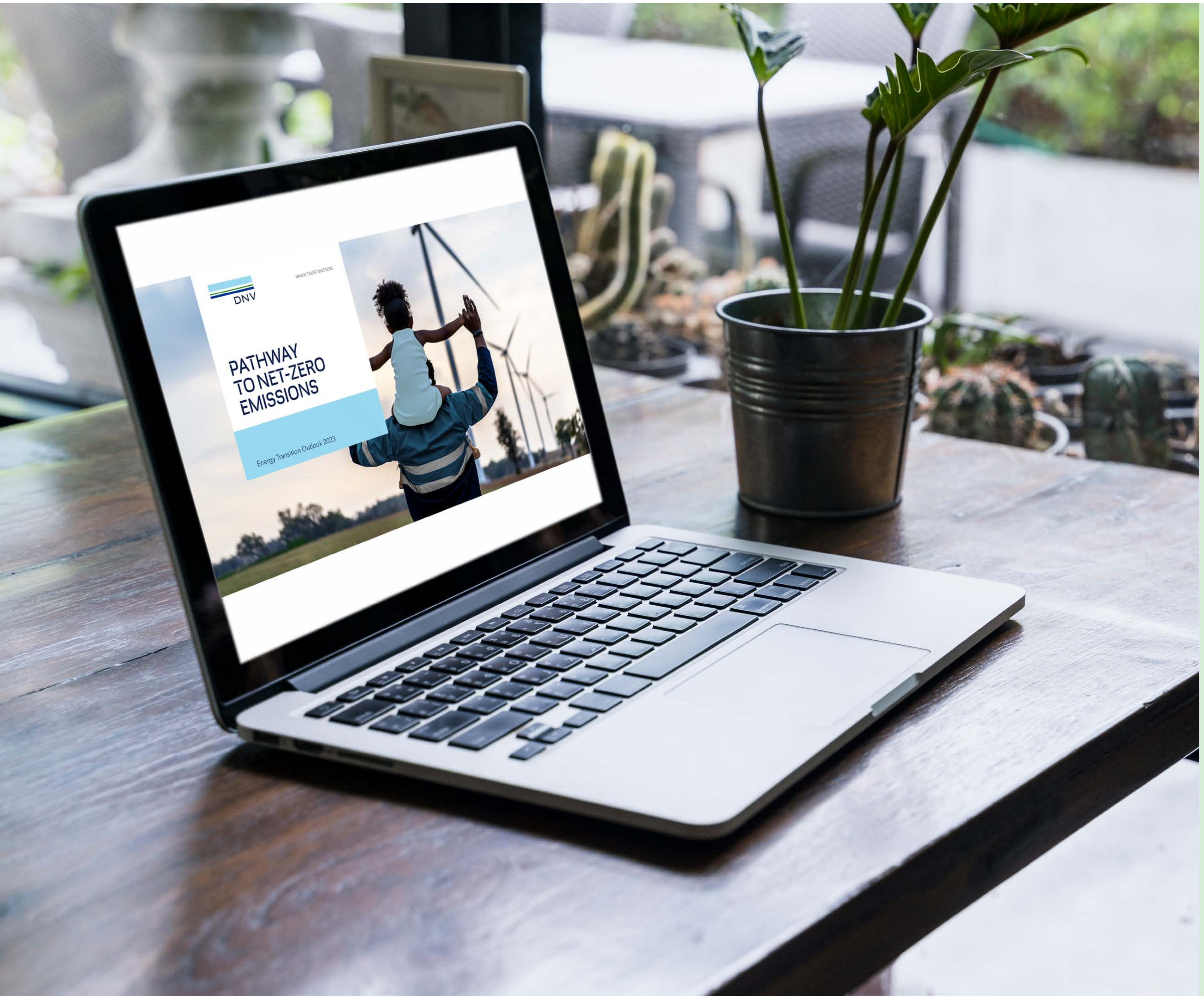
Using the IPCC carbon budgets and the cumulative CO_2 emissions from our forecast, we find that the 1.5°C budget will be exhausted in 2029. The carbon budget associated with the 2.0°C threshold will be exhausted in 2052, outside the forecast period. The CO_2 emissions from energy-related activities as well as industrial process and land-use emissions will still be considerable post-2050 and will continue for many years thereafter. Thus, the question arises: 'What temperature increase does our forecast suggest?'

Our global warming forecast

Our energy forecast ends in 2050, but to analyse the increase and stabilization in temperature all GHG emissions and other climate-forcing changes must be at zero, which is not the case by 2050. Thus, for this purpose we have made an estimate on emissions beyond 2050. Already in 2050, the emissions trajectory shows a relatively steep decline, with increasing amounts of CO_2 captured by CCS. Beyond 2050, our analysis assumes we will arrive at net-zero CO_2 emissions before or at the end of this century – and beyond that perhaps even annual negative emissions (i.e. removal of CO_2 from the atmosphere).

To estimate the CO_2 emissions and global warming by the end of the century, we therefore extrapolate the development of emissions and their capture towards 2100. This will result in increasing amounts of renewables, CCS, and other trends contributing to reduced emissions. Capture occurs only within the sectors shown in Figure 7.4; for sectors such as buildings where there is zero or marginal capture, we let the model determine emission trajectory based on the capacity for emission reductions based on each sector's technology and capacity to switch fuels. This means that we will reach net zero before or by 2100. The approach gives us estimated cumulative emissions of 340 $GtCO_2$ between 2050 and 2100 (Figure 7.10). We do not assume any new technological breakthrough with the potential to significantly disrupt the energy system – such as nuclear fusion or cheap and efficient CO_2 removal technologies – in the second half of the century. With the updated climate response from IPCC AR6 (IPCC, 2021), using the 67% 'likely' overshoot of 330 $GtCO_2$ compared with the 2.0°C budget suggests that global warming will reach 2.2°C above pre-industrial levels by 2100.

> With the updated climate response from IPCC AR6, our forecast suggest that global warming will reach 2.2°C above pre-industrial levels by 2100.



Pathway to net zero

Despite the rapidly unfolding energy transition, our research and modelling finds that the world is most likely heading towards 2.2°C of global warming. That is a dangerous level of warming with catastrophic consequences for humanity and nature. The *Paris Agreement* gave us a clear goal: 'limiting global temperature increase to *well below 2 degrees* Celsius, while pursuing efforts to limit the increase to 1.5 degrees'. Is it possible to accelerate the pace of the transition to secure a future where the global average temperature increase is limited to 1.5°C by the end of the century?

In 2023, DNV published a report called *Pathway to Net Zero* which answered this question and detailed what it would take. Unlike our *Energy Transition Outlook's* main approach, which is a forecast of what is most likely to happen, *Pathway to Net Zero* was a 'backcast' starting from a 1.5°C limit and calculating backwards to find a scenario that would meet this requirement. Obviously, there is more than one way to achieve this, and DNV therefore chose a pathway we think humanity still has a chance to achieve.

The main highlights from *Pathway to Net Zero* were:

- Achieving 1.5°C is less likely than ever, staying as far below 2°C as possible is critical
- Some technologies are powering ahead, others must scale dramatically
- All regions must decarbonize beyond present ambitions, but at different speeds
- Policies must force deep decarbonization in all sectors

DNV found that the only plausible scenario is one with an overshoot in which warming will be above 1.5°C for a while and large negative emissions will be needed in the second half of the century to return to 1.5°C. This is in itself a significant additional risk, but alternatives do not exist from where we are today.

We have not repeated the exercise of producing a 1.5°C scenario this year. The findings from the 2023 report are all still valid, and some have even strengthened. In addition, since broad and urgent action was a prerequisite for meeting a 1.5°C future with an overshoot, and because such action has largely not been seen in the last 12 months, we note that achieving a 1.5°C future is now severely less likely than we found a year ago. We underline that it remains as important as ever to get as close as possible to the 1.5-degree target.

DNV Pathway to Net-Zero Emissions

8

REGIONAL TRANSITIONS

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Highlights

The energy transition unfolds differently in each of the 10 world regions included in our forecast. Its speed and scale are influenced by a number of factors: geographical and resource issues, legacy technology and energy systems, stages of economic development, and government policies.

Thus, every region has a unique starting point and a different transition trajectory – from high-income regions targeting decarbonized prosperity, to middle-income regions comprising fast-growing economies, to regions in an era of development that are addressing energy poverty.

Our ETO model generates insights and captures this granularity. The chapter starts with results, comparing regions on key transition indicators. Thereafter, we cover the transition for each of the 10 Outlook regions, including:

- Current position in terms of natural resource conditions, energy situation, collaboration and climate risks
- Pointers to the future
- The forecast regional transition and resulting emissions

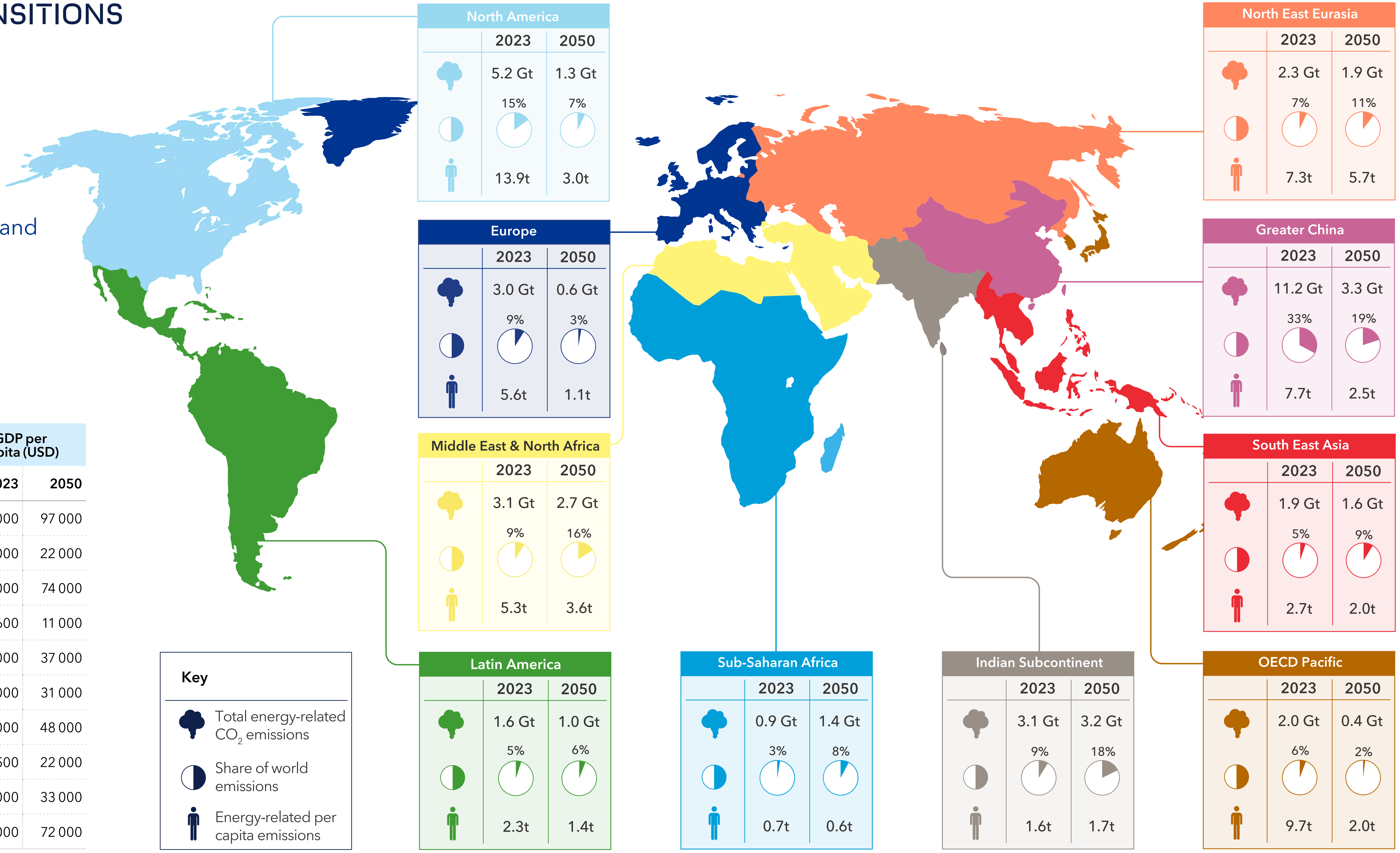
8.0 COMPARISON OF REGIONAL TRANSITIONS

This chapter begins by comparing key transition indicators based on forecast results:

– energy-related CO_2 emissions (shown opposite),
– carbon intensity of primary energy consumption, and
– direct electrification of final energy demand.

We then cover the energy transitions in
10 world regions.

	Population (million)		Energy use per capita (GJ)		GDP per capita (USD)	
Region	**2023**	**2050**	**2023**	**2050**	**2023**	**2050**
North America	376	419	285	195	74 000	97 000
Latin America	669	744	54	55	19 000	22 000
Europe	544	542	125	104	53 000	74 000
Sub-Saharan Africa	1 220	2 140	24	22	4 600	11 000
Middle East & North Africa	575	770	100	98	23 000	37 000
North East Eurasia	320	334	140	122	22 000	31 000
Greater China	1 450	1 340	115	106	24 000	48 000
Indian Subcontinent	1 920	2 230	28	42	8 500	22 000
South East Asia	696	797	48	60	16 000	33 000
OECD Pacific	206	189	173	138	53 000	72 000



Key

●	Total energy-related CO_2 emissions
◐	Share of world emissions
🚹	Energy-related per capita emissions

North America

	2023	2050
	5.2 Gt	1.3 Gt
	15%	7%
	13.9t	3.0t

Europe

	2023	2050
	3.0 Gt	0.6 Gt
	9%	3%
	5.6t	1.1t

Middle East & North Africa

	2023	2050
	3.1 Gt	2.7 Gt
	9%	16%
	5.3t	3.6t

Latin America

	2023	2050
	1.6 Gt	1.0 Gt
	5%	6%
	2.3t	1.4t

Sub-Saharan Africa

	2023	2050
	0.9 Gt	1.4 Gt
	3%	8%
	0.7t	0.6t

Indian Subcontinent

	2023	2050
	3.1 Gt	3.2 Gt
	9%	18%
	1.6t	1.7t

North East Eurasia

	2023	2050
	2.3 Gt	1.9 Gt
	7%	11%
	7.3t	5.7t

Greater China

	2023	2050
	11.2 Gt	3.3 Gt
	33%	19%
	7.7t	2.5t

South East Asia

	2023	2050
	1.9 Gt	1.6 Gt
	5%	9%
	2.7t	2.0t

OECD Pacific

	2023	2050
	2.0 Gt	0.4 Gt
	6%	2%
	9.7t	2.0t

CARBON INTENSITY OF PRIMARY ENERGY CONSUMPTION

Carbon intensity is measured as grams of CO_2 per megajoule of primary energy consumption. It is a good indicator of the energy transition, as it decreases when fossil fuels are phased down from the energy system.

In our forecast, all regions will experience a decline of carbon intensity, showing that the energy transition is a global trend and is not limited to high-income countries. However, the speed of decarbonization will differ among regions.

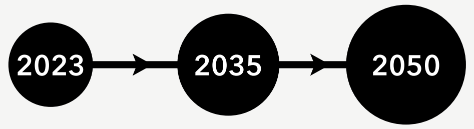
Decarbonization is most rapid in high-income regions. By 2035, Europe, OECD Pacific, and North America see their carbon intensities declining by 80%, 67%, and 65%, respectively.

Greater China will see the largest decrease of carbon intensity. The decline will accelerate towards 2050 as coal is rapidly being phased out from power generation and replaced by renewables. Other regions, like the Indian Subcontinent and South East Asia, will follow the same dynamics. The Indian Subcontinent increasingly relies on renewable energy and achieves huge economic developments while decreasing carbon intensity.

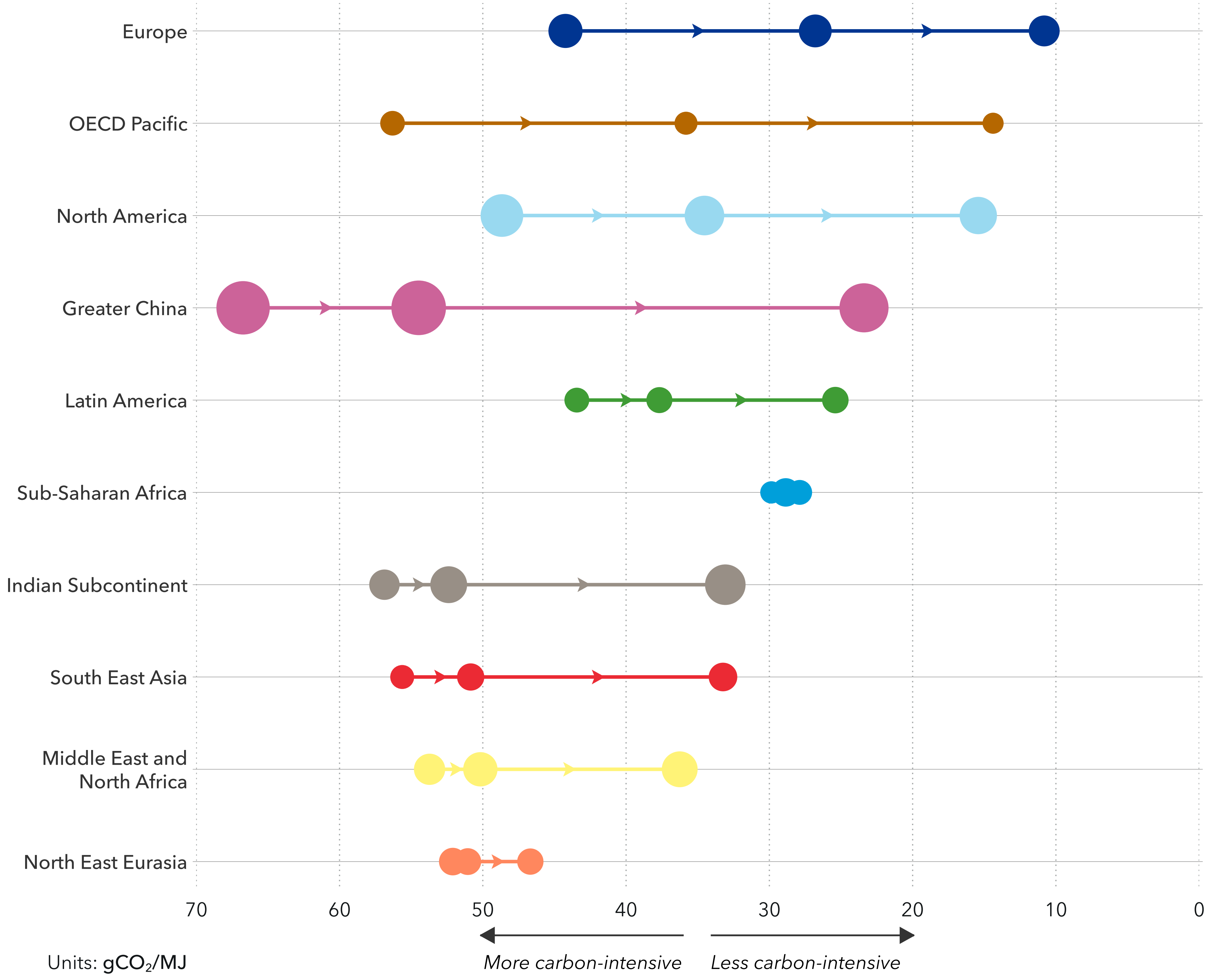
Oil and gas producing regions, North East Eurasia and the Middle East and North Africa, will decarbonize more slowly and have the most carbon-intensive energy systems in 2050.

Interestingly, almost all regions will reach lower carbon intensities than Latin America, the second least carbon-intensive region in 2023. Energy-deprived Sub-Saharan Africa, will see little evolution in carbon intensity. The continued use of traditional biomass, coupled with a slow electrification, means that the carbon intensity will remain stable, at a relatively low level.

Key



Circle area is proportional to total energy consumption.



ELECTRIFICATION OF FINAL ENERGY DEMAND

Electrification is measured as the share of electricity in the final energy demand mix. In our forecast, electrification approximately doubles in all regions, except for North East Eurasia which will remain highly reliant on fossil fuels. Sub-Saharan Africa will also see electrification double, but the total percentage share of final energy demand remains low as the region grapples with grid access issues.

Total final energy demand in 2050 will be lower than in 2023 in all high-income regions and in Greater China. The demand in middle-income regions will remain relatively stable or see some increases like in South East Asia. Both low-income regions, Indian Subcontinent and Sub-Saharan Africa, will almost double their final energy demand from 2023 to 2050. This doubling in demand can be attributed to increased energy access, growing populations, and increased GDP.

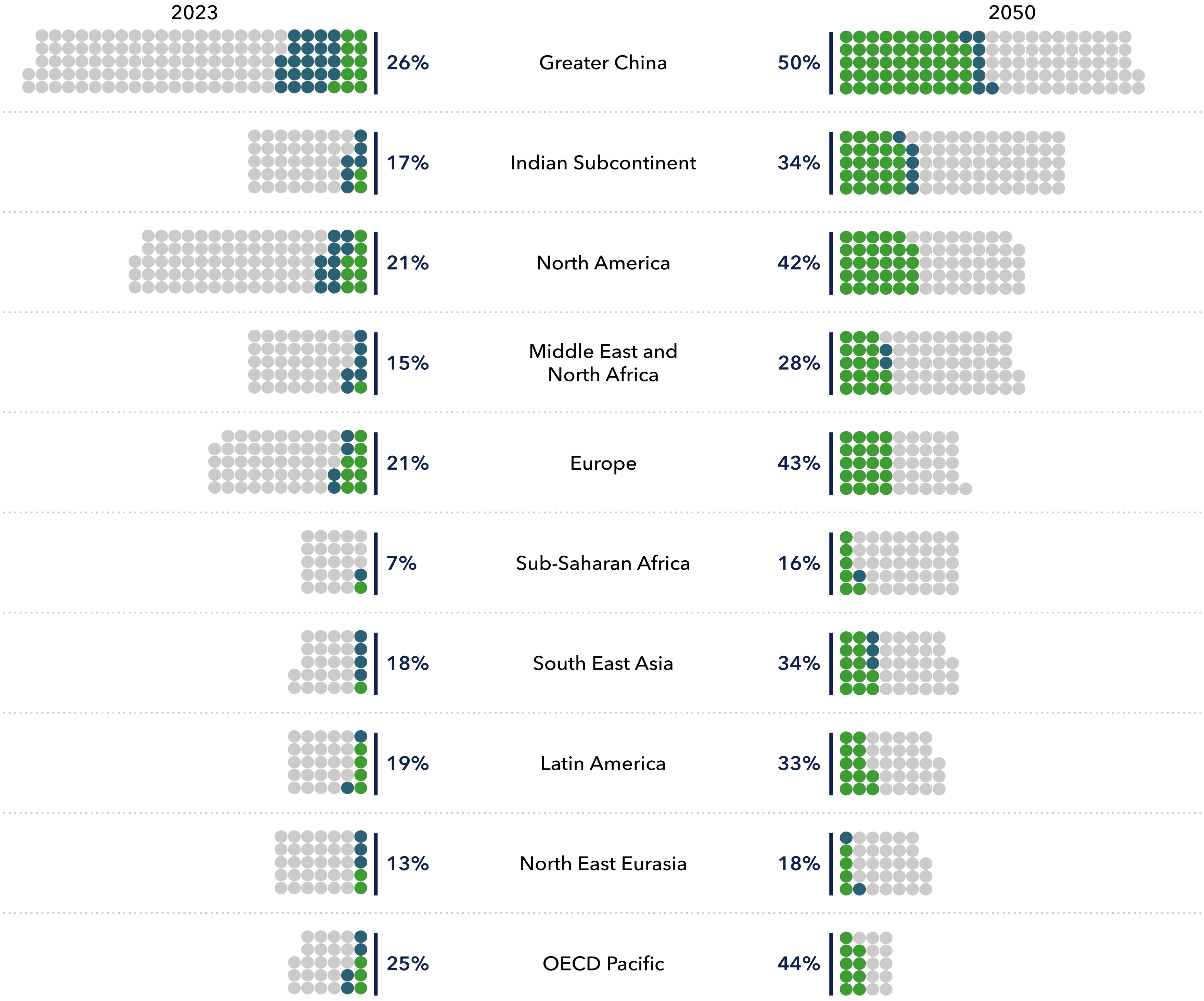
All regions will see a greening of electricity, with a negligible share of electricity from fossil sources in all high-income regions and in Latin America, where the renewables share in power is already high in many countries. In 2050, Greater China continues to lead with a 50% electrification rate, followed by the high-income regions OECD Pacific, Europe, and North America.

Doubling of electrification in Sub-Saharan Africa and the Indian Subcontinent suggests that these regions will 'leapfrog' straight to non-fossil sources of electricity. The share of non-fossil electricity in Sub-Saharan Africa's final energy demand grows from less than 3% in 2023 to over 13% in 2050. The growth is even more visible in the Indian Sub-continent, where the share of non-fossil electricity in final energy demand jumps sharply from almost 4% in 2023 to 28% in 2050.

Key

● Electricity from non-fossil sources
● Electricity from fossil sources
○ Other final demand

Figure accounts for direct electrification. Each circle represents 250 TWh.



8.1 NORTH AMERICA (NAM)

This region consists of Canada and the US.

	Population (Million)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/person (tonnes)
2023	376	28 74 250	107 285	5.2 13.9
2050	419	41 97 250	82 195	1.3 3.3

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.1 NORTH AMERICA (NAM)

Current position

The policy landscape is complex with policymaking at federal, provincial, and state levels. Federal governments in Canada and the US are building clean energy economies and accelerating energy transformations through record-high federal government funding packages.

There is bilateral energy cooperation with the Canada-US Energy Transformation Task Force (ETTF) being renewed (2024) to amplify common priorities in e.g. critical minerals, supply chains, and grids (White House, 2024a). Inter-regional ties deepened, with the US-EU Trade and Technology Council, EU-Canada Critical Raw Materials Partnership, and the Canada-Germany Hydrogen Alliance.

The primary energy supply mix was dominated by fossil fuels at 80% in 2023, and both Canada and the US remain major investors in oil and gas (IEA, 2024; NRCan, 2024a). Power generation was 40% and 80% non-fossil in the US in 2023 and Canada in 2022, respectively.

Announced new US clean energy investments (August 2022 to July 2024) were USD 500bn with manufacturing investments around USD 60bn and realized project investments at USD 75bn (ACP, 2024). Canada's Major Project Inventory (planned/under construction 2023 to 2033) lists 233 clean technology projects (largely renewable electricity and non-emitting energy) representing USD 117bn (CAD 159bn) in potential investment (NRCan, 2024b).

Energy-related CO_2 emissions have peaked and both federal governments have set net-zero GHG goals for 2050 with intermediate reduction targets for 2030 at 50 to 52% below 2005 levels (US) and 40 to 45% (Canada).

Climate-related extreme events are prominent drivers of financial losses in both Canada and the US; in 2023, these exceeded USD 3bn in insured damage in Canada (IBC, 2024) and 28 events in the US with losses exceeding USD 1bn each in 2023 alone (White House, 2024b).

Pointers to the future

- The time horizon of adopted policies suggests willingness to support critical decarbonization technologies and value chains until self-sustaining commercial markets by the mid-2030s.
- Uncertainty arises from the upcoming US presidential election. Incentives already implemented in the US tax code will be difficult to stop without legislative change by Congress. The executive authority could slow or suspend the award of grants, direct spending, loans, and loan guarantees. Some *IRA* support – in clean hydrogen, carbon capture and storage (CCS), nuclear, biofuels – seems politically 'safer' than EVs and redressing socio-economic injustices.
- Overturning *IRA* would undermine private investments and cleantech-manufacturing ambitions. An *IRA* repeal sems unlikely; climate legislation brings federal funding and employment to Republican-controlled states, causing disunity in the party (Dumain, 2024).
- A boost in grid investments, e.g. the *IIJA,* funded (USD 10.5bn) Grid Resilience and Innovation Partnerships Programme recent allocations (GDO, 2024) and the Federal-State Modern Grid Deployment Initiative (White House, 2024c). Canada's Electricity Advisory Council proposes framework development by 2025 for inter-regional transmission projects using the EU's Projects of Common Interest (PCI) as a model (Government of Canada, 2024).
- Policies encourage CCS and direct air capture (DAC) developments. These include Canada's *ITC* applying to CAPEX expenses which supplemented CAD 7bn in *CCfDs* in the event the carbon price trajectory falls, and US *45Q* tax credits. In hydrogen's emission-intensity tiered production incentives, *45V* tax credit guidance (to be finalized) outlines three requirements for producers' electricity consumption (unless 100% renewable): temporal matching (hourly from 2028), incrementality (new generation), and regionality (IRS, 2023).
- Clean hydrogen exports will be subject to emission definitions in e.g. EU *Delegated Acts*, Japan, and South Korea.

Shifting currents: Election, industry, and energy

At the time of writing, the 2024 presidential race continued to be the closest-run contest so far this century. Its outcome will undoubtedly have significant and measurable effects on the trajectory of the energy transition, the clean technology industry, and climate change mitigation efforts.

We have seen this before. In 2017, President Trump withdrew the US from the *Paris Climate Agreement,* while President Biden's first act upon taking office was to rejoin it (Blinken, 2021). Thus, it is unrealistic to believe that, regardless of the election outcome, the progress made through initiatives such as the *Inflation Reduction Act* (IRA) and advancements in climate and clean technology will remain untouched.

In fact, recent history suggests otherwise. The US judicial branch, particularly the Supreme Court, which underwent changes during the Trump administration, has already impacted the clean energy and environmental landscape. For instance, the Supreme Court's decision in June 2024 to overturn the Chevron Doctrine (Howe, 2024) has significantly reduced the power of federal agencies like the Environmental Protection Agency (EPA) to interpret and enforce regulations (Yale School of Environment, 2024). This illustrates how political shifts can reshape the regulatory framework and influence the progress of climate and environmental policies. Furthermore, it reinforces the point about the uncertainty surrounding some of the energy transition narratives we present in this section.

This does not imply that the entirety of the *IRA* will be repealed or significantly curtailed. Research and analysis appropriately indicate that *IRA* funding is being allocated to states across the political spectrum and is enjoying electoral popularity (Denning et al., 2024). Establishing and strengthening clean technology industries in the US and its allies, including Canada, as well as creating energy technology jobs, remains a widely supported policy across the entire political spectrum.

Therefore, it is important to interpret our North American forecast with the understanding that certain technologies and industries may encounter increased challenges based on the outcome of the Presidential election – for instance, EVs may face obstacles due to potential reductions in support (Natter, 2024). Conversely, other technologies and sectors, such as methane reforming-based hydrogen, are likely to continue to receive backing, thereby implicitly supporting fossil fuel stakeholders (Gross et al., 2024).

Current energy superpower

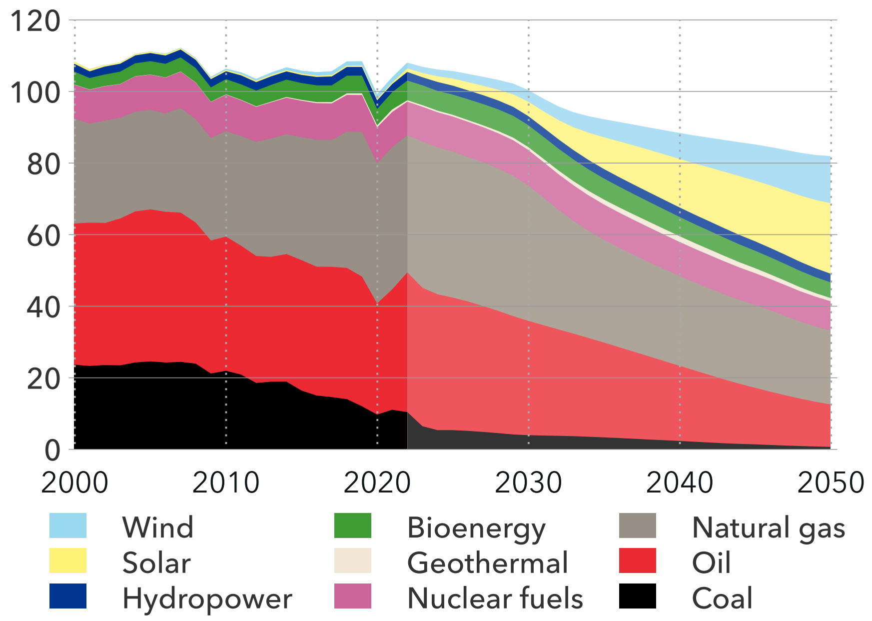
The North American region countries, namely the US and Canada, are conventional energy powerhouses, and will remain so in the future. They have abundant oil and natural gas reserves, coal reserves, uranium for nuclear, and biofuel production capabilities. They will continue to use domestically and export them to other regions in need.

Even in 2023, North American primary energy consumption was fossil-fuel heavy; coal, oil and natural gas combined to make up 80% of the energy mix (Figure 8.1.1). Even more remarkable was the fact that North America is a net exporter of coal and natural gas and will continue to be a net exporter of natural gas for the foreseeable future (Figure 4.10). The fossil fuel energy reserves in North America can be commanded when the need arises.

FIGURE 8.1.1

North America primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2024)

The need to shore up allies has meant that North America did not hesitate to step in with critical natural gas exports to Europe and a release of its strategic oil reserves (US Department of Treasury, 2022) after the invasion of Ukraine by Russia. Conflict and related disturbances in the Red Sea ports in 2023 has also meant that the Middle East and North Africa natural gas exports declined in 2023, paving the way for North America to be the primary natural gas exporter across the globe.

Subsequently, North America exported the highest quantity of natural gas in the world in 2023. We forecast approximately 80% of North America's natural gas exports going to Europe in 2030. The ability to ramp up LNG exports to Europe has also been possible due to the existing liquefaction plants in the Gulf of Mexico and the Eastern seaports in Canada, and the ability to double them in a short time (EIA, 2024). While the risk of stranded assets (ClientEarth, 2024) is a reality when it comes to fossil fuel infrastructure, the ability to convert fossil fuel infrastructure to support hydrogen or ammonia is a potentially viable option (Samuel et al., 2023). The business decision to develop new infrastructure at least seems a reasonable one, despite the risk.

The stronghold of fossil fuel on the primary energy mix is a manifestation of both system- and infrastructure-related and socio-political inertia in the region, with many decades of fossil-fuel dependence in key demand sectors (EY, 2023). This makes the transition we envision for North America all the more remarkable.

Watt's up, North America

In 2023, solar and wind combined had a share of 3% in the primary energy mix. We project this share will more than double to 7% by 2030. By 2040, the penetration of solar and wind will further grow to 24%, and it will reach 40% by 2050. In absolute primary energy terms, this is a staggering 10-fold growth. Consequently, the decline in fossil fuels we forecast ensues. As electrons take over the energy mix, carbon molecules grow less important (Figure 8.1.2). By mid-century, fossil fuels will have an equal share with the combination of solar and wind in the primary energy mix, a share of 40% each.

This growth in solar and wind is possible due to increasing electrification. Electrification of demand sectors that can be electrified is the first step to decarbonizing the energy system (DNV, 2023a). The share of electricity in the final energy demand of the three major demand sectors – manufacturing, buildings and transport – all increase, leading to a corresponding reduction in fossil fuels (Figure 8.1.3). While the starting points in terms of electricity shares are very different in the three sectors, they are all projected to increase. In the case of buildings and manufacturing, the growth is 1 to 2% per year, while transport, starting from a very small base in 2023, sees a staggering 14% growth per year.

Increasing electrification changes the final energy demand of North America as a whole. From 2023 to 2050, we forecast that electricity's share in the final energy demand of North America will double, from 21% to 42% (Figure 8.1.4). At the same time, final energy demand reduces from 80 EJ/yr in 2023 to 62 EJ/yr in 2050, a 1% average annual reduction.

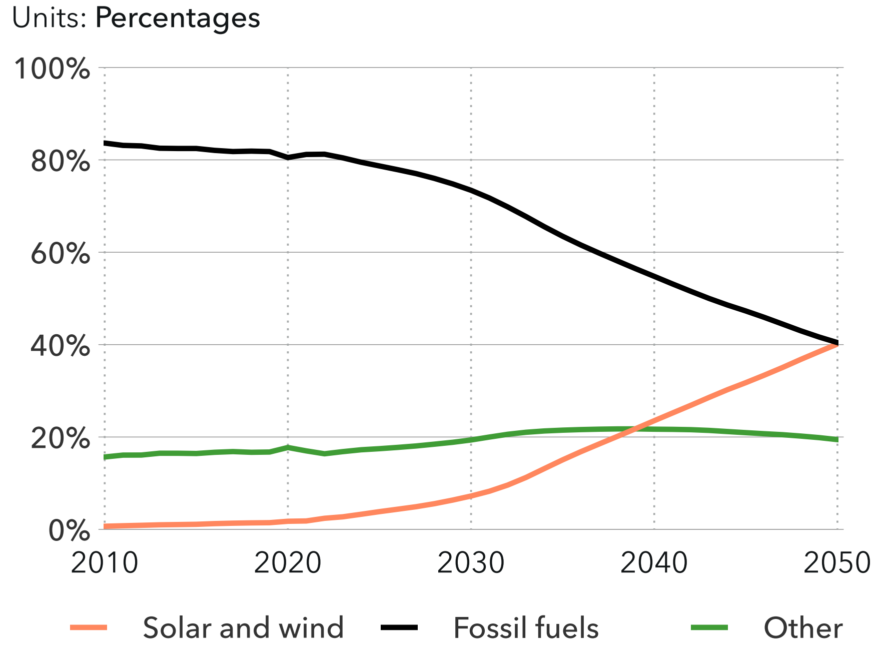
This is possible because of:

- The electrification of road transport.
- Advances in energy efficiency, such as better insulation of buildings, and technological advances in manufacturing technologies, such as multi-stage high-heat boilers.
- Penetration of energy amplifying technologies such as heat pumps in buildings and manufacturing (for low temperature heating).
- Electrification itself, with electricity being a more efficient or 'higher exergy' energy source, when compared with natural gas, oil or coal (Sejkora et al., 2022).

The cumulative effect of these efficiencies means that even while final energy demand decreases in our forecast, the useful work or services provided by that energy in North America increases from

FIGURE 8.1.2

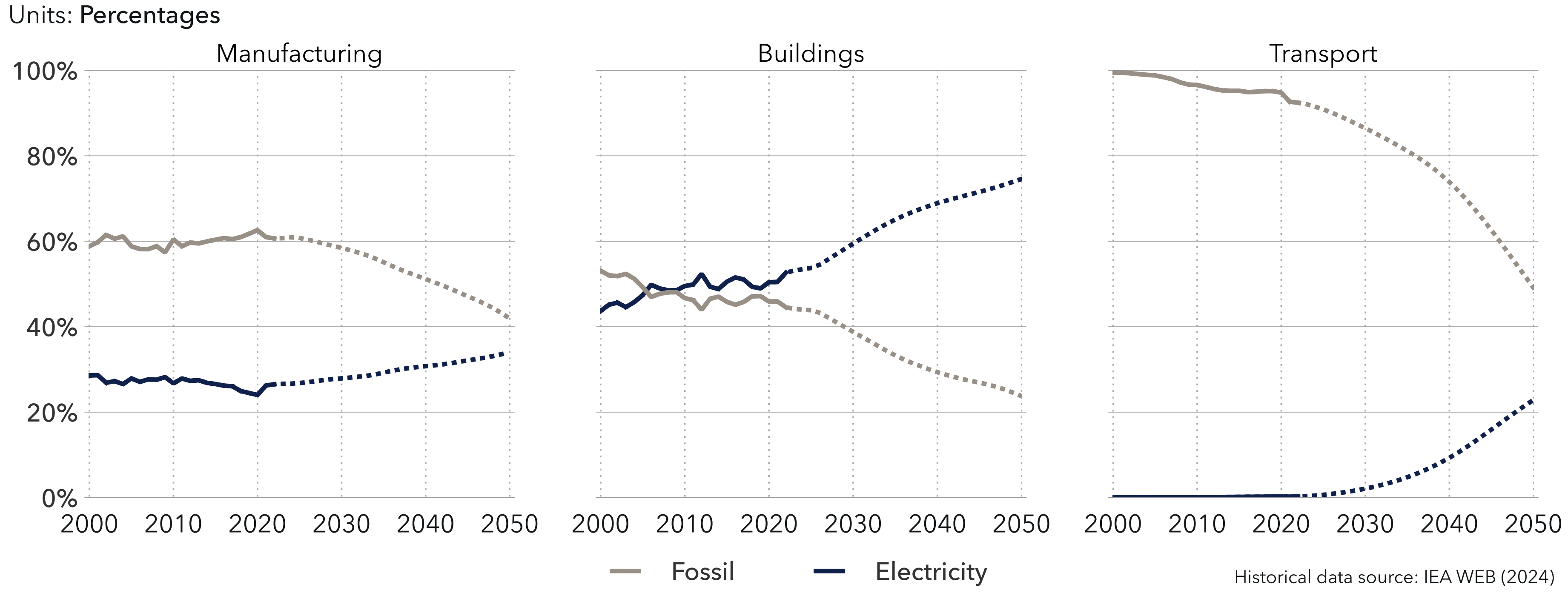
Shares in primary energy consumption in North America



Historical data source: IEA WEB (2024)

FIGURE 8.1.3

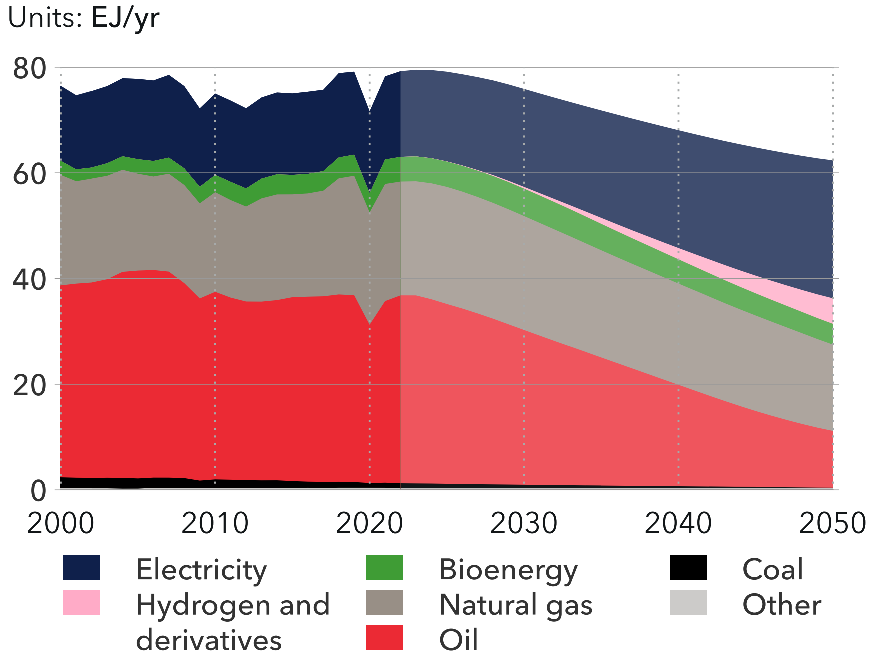
North America shares of electricity and fossil fuels in major demand sectors



Historical data source: IEA WEB (2024)

FIGURE 8.1.4

North America final energy demand by carrier



Historical data source: IEA WEB (2024)

60 EJ/yr to 67 EJ/yr within the same period. This illustrates the potential of electrification of demand sectors to completely revolutionize an energy system, even one as complex and diverse as the North America's.

Electrify, electrify, electrify

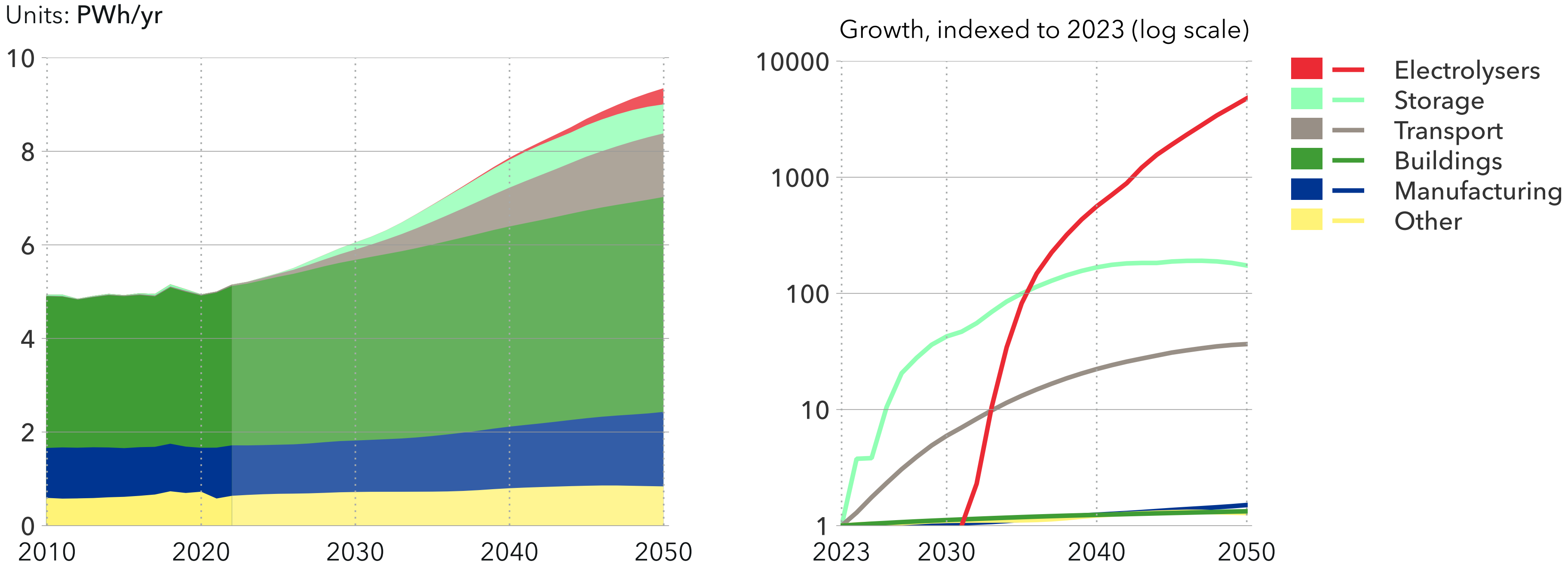
This electrification drive we envision also drives up the demand for electricity. Between 2000 and 2020, electricity demand in North America remained stagnant. We forecast this picture changing dramatically, however, and already saw signs of that happening in 2022 and 2023. The demand in 2023 for electricity was higher than in pre-pandemic 2019. In the next 27 years, we forecast that the electricity demand will almost double in North America, from 5,200 TWh/yr in 2023 to 9,400 TWh/yr by 2050.

This electricity demand growth from 2023 to 2050, pegged to the values in 2023, is shown on the left side of Figure 8.1.5. This presents the growth in different demand segments in a log-scale, and points to the two mechanisms driving the growth.

The first mechanism is the further electrification of existing demand, such as buildings, manufacturing, and transport. The growth of transport sector electricity demand is much higher than buildings and manufacturing, thanks to the rise of EVs we forecast in North America and the small amount of demand overall in 2023 in the region.

FIGURE 8.1.5

Electricity demand in North America



Electrolysers are indexed to 2031. Historical data source: IEA WEB (2024)

Here, it is important to stress that, after multiple years of stagnant growth in buildings, the rise of electricity demand for AI, data centres, and crypto currency mining leads to a 33% growth from 2023 to 2050. This is despite the trend of demand and use of commercial buildings going down after the COVID-19 pandemic. In the US especially, we expect AI and data centre electricity use to grow quickly to keep up with the rapid deployment of large language models and the ensuing data storage and model training energy needs (Howland, 2024). In our current forecast, data centres and the like are modelled as commercial buildings and not as a category of their own. But given the rise in their energy needs, we may have to forecast their energy demand separately in the coming years.

The second mechanism is the introduction of two new demand categories. The first is the electricity demand of grid-connected storage, chief of which is the Li-ion batteries (Figure 8.1.5). Second is the electricity demand of grid-connected electrolysers that produce hydrogen. Both demand segments are in their infancy now, but we forecast they will explode in demand.

In the case of energy storage and Li-ion batteries, growth is spurred on by the need for short-term storage in the grid as a flexibility measure when more variable solar and wind power are added. Energy storage is critical to smooth out short-term variations in power production and to mitigate against the many hours that have zero electricity prices due to the low marginal costs of solar production. Concurrently, the IRA has also introduced a Battery Storage Tax Credit for standalone grid connected batteries (White House, 2023), which is expected to stimulate the battery additions in the grid. In California's grid, with its a high penetration of solar PV, we already see signs of Li-ion batteries playing a critical role during late evenings in summer months as solar PV generation drops, replacing gas-fired generation (Chediak, 2024).

The many hours of very cheap electricity that will be prevalent with more solar energy production in the grid will incentivize electrolyser operation. Essentially, the electrolyser will act as a grid-balancer, providing load when electricity is cheap, by converting that low-cost electricity to a more valuable energy medium: hydrogen. More in-depth analysis of this electrolyser operation in North America is presented in DNV's (2024) *New Power Systems* report.

The growth in electricity demand forecasted for North America presents an unprecedented readiness to exploit the myriad business opportunities price arbitrage may present. The first to move to provide a load balancing service, or capacity provision through batteries, will be able to capture the 'other services' market in addition to providing the kilowatt-hours.

Sun and wind powering growth

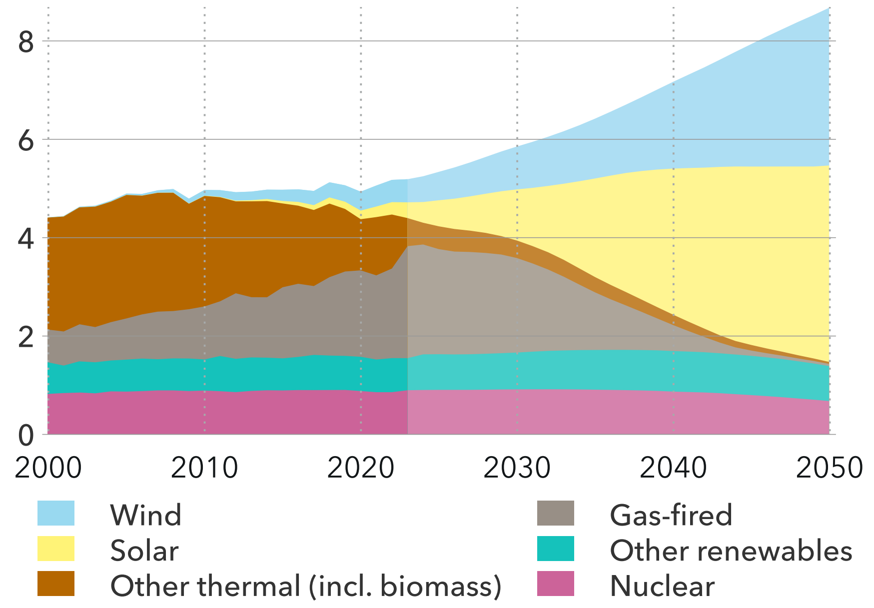
The increase in demand in the next three decades implies that the grid-connected electricity generation will grow in lockstep (Figure 8.1.6). More importantly, most of this new growth is going to be through wind and solar.

In 2023, most of North America's electricity generation was through gas-fired power plants (44%) with coal and oil providing a combined 10%. However, the North American coal fleet is an ageing one, expected to be replaced within the decade. With aggressive state-based ambitions of decarbonizing the grid, this coal generation is also going to be replaced by solar and wind.

FIGURE 8.1.6

North America grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

We expect to see new demand being supplied by renewables and replacing coal. In the 2030s, part of North America's gas-fired generation will near retirement age and will struggle to compete on cost with cheap solar and storage and wind in many grids.

Solar energy is the most cost-effective electricity generator in many regions across North America right now. State-level policies, along with production and investment tax credits from the IRA, further enhance the competitiveness of solar when compared to gas-fired power plants. These incentives also make wind energy equally competitive.

Starting in the 2030s, we anticipate that solar and wind will make significant inroads into the North American grid, meeting new demand and replacing conventional power generators. In addition, the cost-effectiveness of these renewables will lower electricity prices across key demand segments, creating a positive feedback loop where cheaper electricity boosts demand, leading to increased supply.

Between 2010 and 2020, an average of 8 GW of solar PV and onshore wind capacity was added annually. Over the next decade, onshore wind capacity additions are expected to double, while solar PV capacity additions will more than triple (Figure 8.1.7).

In addition to onshore wind, between 2040 and 2050, about 10 GW of fixed offshore wind is set to be installed in the Eastern seaboard of the US and Canada. These capacity installations are motivated by the decarbonization goals of states on the East Coast of the US that are looking to offshore wind for clean electricity due to land constraints inland.

Between 2040 and 2050, we forecast that solar PV installations will slow down and be overtaken by solar PV co-located with storage, since it will present better capture prices and profitability in a grid that already has significant solar PV generation.

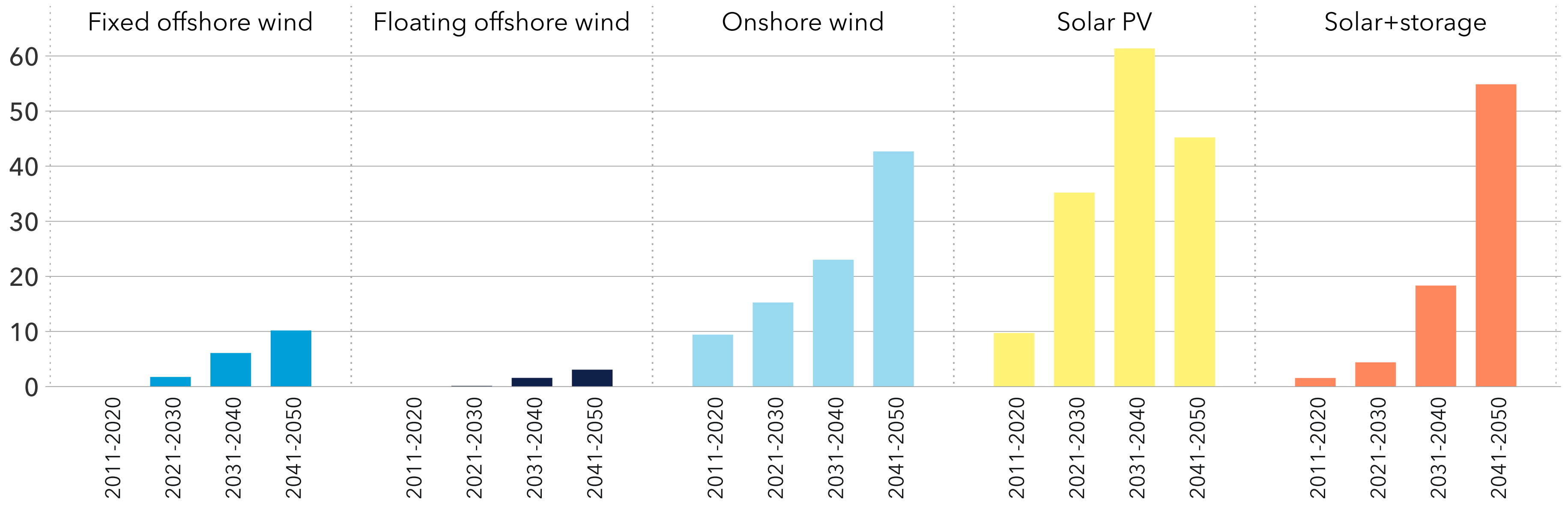
The integration of this vast variable renewable energy source (VRES) capacity highlights the critical need for energy storage and a robust, efficient grid. In recent years, delays in the interconnection and permitting processes have drawn attention, underscoring the challenges inherent in transitioning from a thermal-dominated electricity grid to one dominated by VRES. While the gridlock is still severe in many grids, positive signs of an easing have emerged with the passing of the *Energy Permitting Reform Act* of 2024, a critical piece of legislation meant to shorten permitting times for both electricity and other energy grids, such as natural gas (Robinson et al., 2024).

> By 2050, we forecast that solar will generate 46% of North America's electricity, with wind contributing 37%, resulting in a 99% carbon-free grid. However, achieving this growth will require substantial new capacity.

FIGURE 8.1.7

Average yearly grid-connected wind and solar capacity being added in North America

Units: GW/yr



Historical data source: Global Data (2024)

A new kind of energy (in)security

The future revolution and/or transition of the power and demand sectors has one thing in common: the need for clean energy technologies such as solar PV panels, wind turbines, Li-ion batteries, and EVs.

However, North America is not best positioned to produce these technologies. The well-documented deindustrialization of North America in the opening decades of this century (Atkinson, 2024), saw the region cede the lead in manufacturing clean energy technologies, such as solar panels and batteries, to other countries and regions of the world, principally, of course, China.

The region is thus having to navigate the geopolitics of trade of clean technologies from a less advantageous position (Ince et al., 2023). This means North America is now dependent on regions outside its sphere of influence for its energy transition – in effect a new kind of energy insecurity.

Reactions to this developing energy and geopolitical insecurity have been protectionist in nature, with the following broad objectives:

- Lessen their dependence and vulnerability on countries such as China (Ince et al., 2023).
- Increase national and energy security.
- De-risk clean energy technology supply chains.
- Create local jobs and increase secondary sector value creation.

> Clean energy technology leadership will be a new opportunity for North America, however poses short-term risk of increasing the cost of energy transition in the region.

What North America, and specifically the US, has done to rectify this situation has both 'pull' and 'push' elements. To encourage and 'pull' local manufacturing of these technologies, it provides significant tax credits to firms moving their clean energy technology manufacturing facilities to the US through the 48C provision in the *Infrastructure Investment and Jobs Act* (IIJA) (US DOE, 2023). Similarly, the IRA gives extra tax credits to clean energy technologies manufactured domestically, which are not available for imported clean energy technologies in an energy production project (DNV, 2023b).

On the push side, to make local manufacturing competitive compared with imports from regions which have had decades of experience in producing clean energy technologies, and high levels of government subsidy and support, the US and Canada have imposed import tariffs on these products from those regions. The tariffs imposed are most notably on solar PV panels with a tariff range of 14.5% to 286% (with anti-dumping provisions), EVs with a tariff range of 25% to 100%, and Li-ion batteries with a tariff range of 7.5% to 25% (White House, 2024d).

In the near term, the costs of technologies like solar PV and batteries are expected to rise for project


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

developers, as local production will take years to establish. Transitioning an entire supply chain will be a gradual process. Additionally, it will take time for 'learning by doing' to bring costs down. Between 2024 and 2044, we anticipate a temporary cost increase of 10 to 20% CAPEX for EVs, batteries, and solar PV, even with tax incentives under the IRA and IIJA. This also aligns with industry projections (Murray, 2024; Ford, 2024).

These developments present an opportunity for market players in regions such as Latin America to become valued trading partners of clean energy technologies with North America, while also increasing and developing manufacturing capacity in their respective regions. In theory, it also increases the resilience and diversity of these clean energy technology supply chains, which is a common good. North America is, essentially, aiming to break up the quasi-monopoly that currently exists in the production of critical clean energy technologies (Eco-Business, 2024; Gordon et al., 2024).

In the short term, this will lead to an increased cost of the energy transition and a possible slow-down of the speed of the energy transition in North America. So far, the region appears willing to absorb this consequence in return for long-term energy, geopolitical security, and self-sufficiency.

The developments we foresee are not straightforward. The idea of moving clean energy technology supply chains to North America is not set in stone, especially because of the impending election (November 2024) and the impact it will have on tax credit policy. There are already signs that IRA-incentivized manufacturing projects are getting delayed, as firms wait to see how the election will shape up and are hard hit by high interest rates and cost of capital (Chu et al., 2024). Moreover, tariff-induced cost hikes in clean tech components are already having a dampening effect on end-use demand for EVs and solar installations; passing on tariff costs to consumers may harm the industries they aim to protect.

In the meantime, North America will continue to strive to improve their core competence in other clean fuels and energy carriers such as hydrogen, where no other region has yet established a dominant position. Yet even here, blanket tariffs on Chinese goods may harm the sourcing of electrolyser componentry and lead to higher costs for hydrogen companies in the US in an industry where capital costs are already an issue. Under such a scenario, it would be vital that the tax credits available under the IRA of up to USD 3/kgH$_2$, remain in place after the forthcoming election.

Different molecules become important

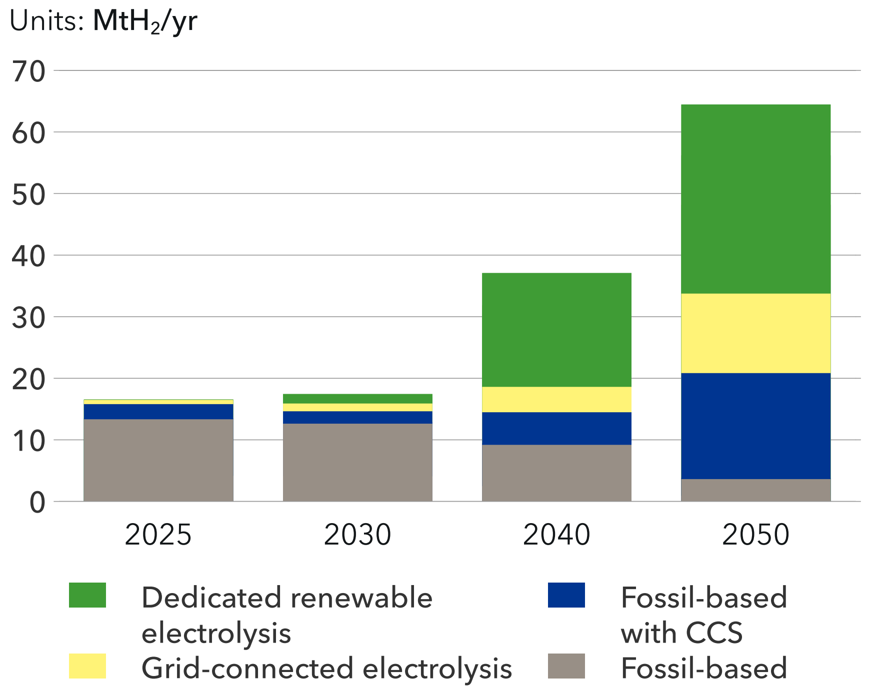
While electrification is a clear-cut path to decarbonization, there are hard-to-electrify sectors which need molecule-based solutions. In North America, we forecast hydrogen will become that molecule of choice. This is based on the multiple tax credit provisions of the IRA, such as 45Q which incentivizes methane-reforming hydrogen with CCS, and 45V which incentivizes the production of very low GHG-emission hydrogen (DNV, 2023b).

The total hydrogen demand in North America in 2023 was about 17 Mt/yr, mostly for use in oil refineries, and most of it produced domestically. The overwhelming majority (84%) of this hydrogen production was by fossil-based means, mostly through steam methane reforming (Figure 8.1.8). By 2030, thanks to the incentives of the IRA, we expect fossil-based productions coupled with CCS (6%) to start making inroads along with hydrogen from grid-connected electrolysers (7%).

In the period from now to 2030, blue hydrogen – produced by methane-reforming coupled with CCS – will play a critical role in the region. Allowing the use of existing technical know-how in methane reforming in the fossil fuel industry, as well as the CO$_2$ infrastructure that North America possesses, will stimulate demand through relatively cost-effective supply.

FIGURE 8.1.8

North America hydrogen production by production route



This blue hydrogen production is also critical due to the near-term challenges of renewable hydrogen. Since the IRA requires additionality – that is the electricity for producing this hydrogen should be additional renewable electricity, not taken from satisfying existing demand – the project should have its own renewable power source. At present, such projects are few, especially with no guaranteed demand.

However, by 2040, the cost calculus of renewables such as solar and wind will be so beneficial that electrolysers coupled with dedicated wind and solar power plants will start producing most of the hydrogen needed in North America. By 2050, grid-connected electrolysers will produce a fifth of the hydrogen demand. This production will play a critical role in balancing the North American grid, as highlighted previously in this chapter.

One critical risk that the hydrogen sector faces in North America is that decarbonized hydrogen is too expensive even now, hence the industries that have to use hydrogen are not demanding it. Investors are therefore hesitant to invest in clean hydrogen production plants, thus stymying the entire industry. One measure taken by the federal government to counteract this reluctance is to establish Clean Hydrogen Hubs and stipulate strict emission standards for 'clean hydrogen', thus stimulating both its production and demand. In addition, decarbonization targets in hard-to-abate sectors, such as

high-heat manufacturing and aviation, also stimulate demand for clean hydrogen and send a strong signal for investment.

Still not enough to be carbon free

Despite the IRA, IIJA, and investment stimulus for clean energy technologies, the North American region does not reach zero emissions by 2050.

By mid-century, the energy sector and industrial processes still emit 1.4 $GtCO_2$ (Figure 8.1.9), despite CCS and DAC capturing a combined 350 $MtCO_2$/yr.

This is a sobering finding by itself. That the most comprehensive clean-energy investment funding in a century, driven by the richest region, cannot completely eliminate CO_2 emissions from the energy sector is a signal that rapid decarbonization is very difficult to achieve without a comprehensive cost on carbon. In oil-producing US and Canada, carbon pricing is a heavily politically charged issue, unlike, for example, the EU where decarbonization is far more comprehensive by 2050.

In the short term, and in the context of country pledges in nationally determined contributions (NDCs) under the *Paris Agreement*, the US has a target to reduce net GHG emissions by 50 to 52% by 2030 compared to 2005, and Canada is committed to a 2030 target of 40 to 45% below 2005 levels. Compared with 1990 emission levels, to have a common reference point for all regions, North America is targeting a 2030 reduction of 38%. By 2030, we forecast a reduction of 35% in energy and industrial process-related CO_2 emissions, compared with the peak 2005 emissions. In effect, we forecast that the IRA will not achieve the objective of reducing emissions by 40% in 2030, compared with 2005.

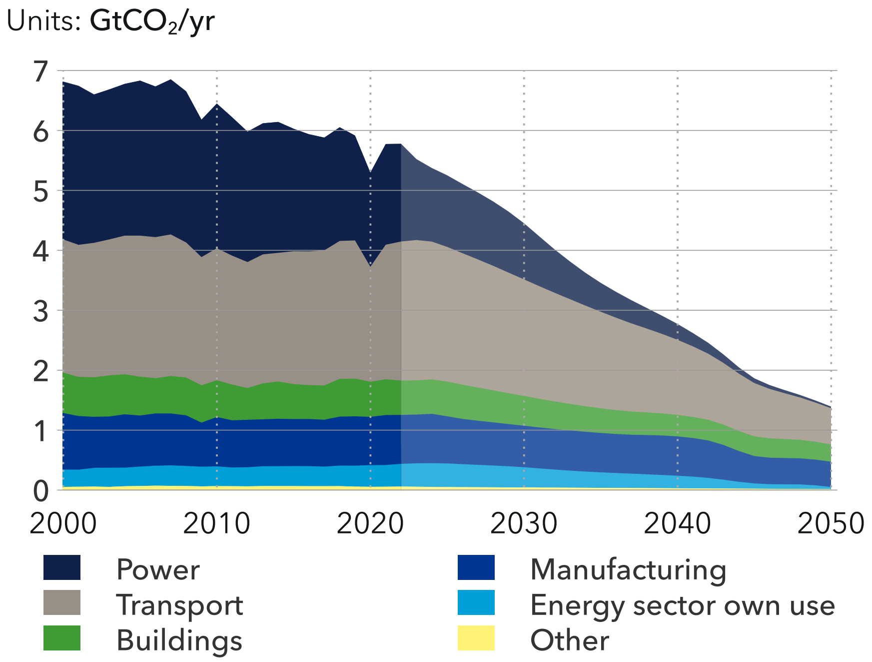
The sector with almost half of the remaining emissions is transport (600 $MtCO_2$), mostly because aviation and maritime are hard-to-abate sectors and the alternatives of decarbonizing them, such as SAF and ammonia and methanol, will still be more expensive than emitting carbon.

Furthermore, despite North America's decades of experience capturing carbon, CCS capacity in the US is not going to ramp up fast enough to capture the remaining emissions. This is despite the USD 180/tCO_2 incentive for DAC in the IRA.

The remaining emissions in North America therefore reinforce the need for a price on carbon, as part of the US federal level policy mix as a measure to complement the clean energy incentives of IRA. This would put a penalty on CO_2 emissions and is particularly important to create uptake and market deployment certainty for low-carbon alternatives. Policies in both directions – incentivizing clean energy and de-incentivizing carbon emissions – are needed for an effective decarbonization of the energy system. We forecast that relying solely on incentives to decarbonize the energy sector will not decarbonize the region fast enough to limit global warming to 1.5°C.

FIGURE 8.1.9

North America energy-related CO_2 emissions by sector



Historical data source: IEA WEB (2024)

8.2 LATIN AMERICA (LAM)

This region stretches from Mexico to the southern tip of South America, including the Caribbean island nations.

Brazil, Argentina, Mexico, Colombia, Chile, and Venezuela account for **80%** of the region's energy use.

	Population (Million)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/ person (tonnes)
2023	669	12.4 18 500	36.2 54.1	1.6 2.3
2050	744	21.5 28 900	41.2 55.4	1.0 1.4

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.2 LATIN AMERICA (LAM)

Current position

The region has large export-oriented primary industries like fossil-fuel extraction, mining, and agriculture. Brazil, Venezuela, and Colombia are leading oil exporters, while Chile and Panama are highly import-dependent countries.

Latin America has approximately 20% of global oil reserves, 25% of strategic metals, and more than 30% of the world's primary forests (ECLAC, 2023). Rich natural resources provide excellent conditions for energy projects in biomass, hydro, solar, and wind. Competitive tendering has brought impressive growth in non-hydro renewable generation.

Subregional efforts, aided by the Inter-American Development Bank, promote power infrastructure interconnection (IDB, 2024) and the RELAC initiative joins 16 countries in pursuing 70% renewable electricity by 2030 (Paredes et al., 2023). Inter-regionally, EU Global Gateway investments (USD 49.5bn by 2027) has green transition at its core (Diaz-Granados, 2023). China's presence has climbed through BRI with approximately USD 10bn to generation and distribution projects since 2000 (Myers, 2023). China is a top export destination for Brazilian, Chilean, Panamanian, and Peruvian minerals.

Along with economic and population growth, energy demand is growing. Renewables produce 30% of energy supply and hydrocarbons produce 70%, of which oil accounts for 41% (2023). Overall, energy-related CO_2 emissions have peaked; their largest driver is transport. Larger economies, Argentina, Brazil, Chile, and Colombia have carbon-neutrality targets by 2050.

Climate-change effects include sea-level rise, loss of glaciers, storms, abnormal rainfall, floods, and fires. Drought-induced acute water crises undermine hydropower output. The economic damage associated with disasters attributable to climate over the past two decades is estimated at over USD 170bn (EIB, 2023).

Pointers to the future

- The region is well positioned to limit power emissions. Rising VRES targets underpin road transport electrification where Brazil, Costa Rica, Colombia, and Mexico have incentives. Mexico is also positioned for EV manufacturing capacity driven by a 'nearshoring boom' close to the US market.
- Battery energy storage systems are set for growth to alleviate curtailment and zero pricing, such as in Chile's Atacama Desert where solar projects will pair with storage. However, the low flexibility of thermal power and transmission capacity potentially delays Chile's coal phase-out to 2040.
- In general, the region needs better-connected grids to support storage and transport of renewable electricity (Mehlum, 2024). Advances in buildout is seen in Brazil with multiple UHV project contracts to China's State Grid (Esteban, 2024).
- Colombia's first offshore wind round (2024) aims for up to 3 GW. Brazil's regulatory framework for offshore wind awaits approval, while the *Nova Indústria Brasil* (NIB) plan, inclusive of CCS and BECCS priorities, was approved in early 2024.
- Argentina's hydrogen strategy targets 5 Mt low-carbon production by 2050 with 20% for domestic use. Chile will announce incentives (2025) for its *Green Hydrogen Action Plan 2023-2030*, and Brazil's *Hydrogen Act* creates the legal framework for low-carbon hydrogen and tax credit incentives between 2028 and 2032, prioritizing domestic consumption. Renewable hydrogen industry aspirations are aided by EU Global Gateway funding.
- Mexico's 2024 election suggests energy policy continuity with a dominant role of state-owned Federal Electricity Commission (CFE) and Petróleos Mexicanos (Pemex), but the president-elect pledged to be more supportive of transition and renewables.

Energy transition: succeeding with solar and wind, but lagging in hydrogen ambitions

Latin America has vast access to natural resources. This is reflected in the energy mix of the region, with wide access to both fossil and non-fossil energy sources. Most of the electricity generation already comes from renewable sources and the transition away from fossil fuels moves quickly in this part of the energy sector. However, the full picture is not as green, as almost half of the total energy demand will still be covered by fossil fuels in 2050. There is resource potential for a faster transition, but it is contingent upon more expedient development of regulatory frameworks and conducive incentives that address environmental licensing hurdles, indigenous resistance, flexibility, and electricity network expansions.

Over the past decade, Latin America's final energy demand has shown little change, indicating only modest improvements in living standards across the region. However, we expect that after 2025, rising per capita income will lead to a 27% increase in the region's final energy demand between 2023 and 2050 (Figure 8.2.1). We project 86% of this additional demand will be met through increased electricity generation, which we anticipate to more than double during this period. As a result, we expect the proportion of electricity in the region's final energy demand to increase significantly, from 18% to 33%.

Renewable energy sources are poised to become increasingly crucial in shaping Latin America's energy future. By 2050, we expect the share of renewables in the region's primary energy demand to rise from around 29% today to over 52% (Figure 8.2.2). While biomass and hydropower – currently the leading renewable energy sources – will continue to play significant roles, most of the growth in renewables will be driven by solar PV and wind power.

Use of oil, the region's largest source today, will only decline after 2040. Growth in the use of natural gas for energy will stall soon and will not overtake oil as the largest primary energy source within the forecast period (Figure 8.2.2), with the two fuels meeting 16% and 31% of the final energy demand, respectively. In contrast, coal and nuclear energy will remain only minor contributors to Latin America's overall energy mix.

Energy demand: fuelled by rising standards of living

Energy demand in Latin America will grow the most in manufacturing (52%), especially due to a production increase in manufactured goods and base materials that will happen as the GDP per capita grows (Figure 8.2.3).

Energy use for buildings will increase by 42%. Such an increase reflects the spread of heating and cooling services to new segments, driven by a combined effect of rising living standards and growing population, and powered predominantly by electricity.

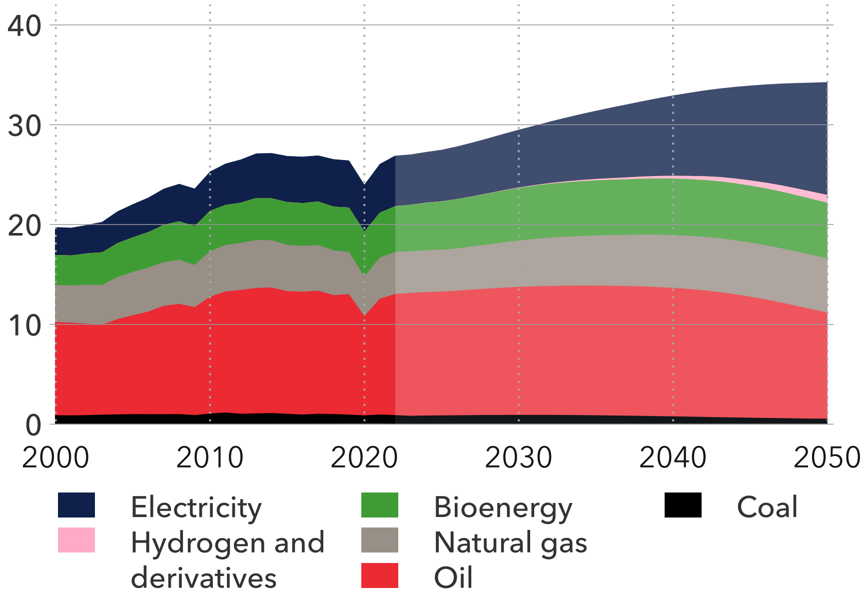
In the transport sector, increasing electrification will absorb the vehicle fleet expansion such that the energy demand for transport will come to a halt and then reduce from 40% to 30% of the total energy demand.

> More than half the region's energy demand will still be covered by fossil sources in 2050, but there is potential for a much faster transition.

FIGURE 8.2.1

Latin America final energy demand by carrier

Units: EJ/yr

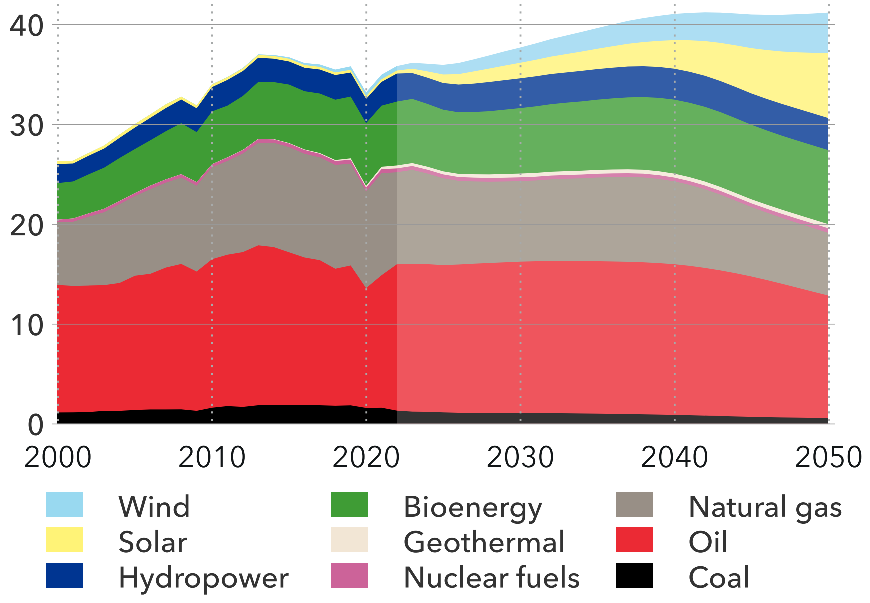


Historical data source: IEA WEB (2024)

FIGURE 8.2.2

Latin America primary energy consumption by source

Units: EJ/yr

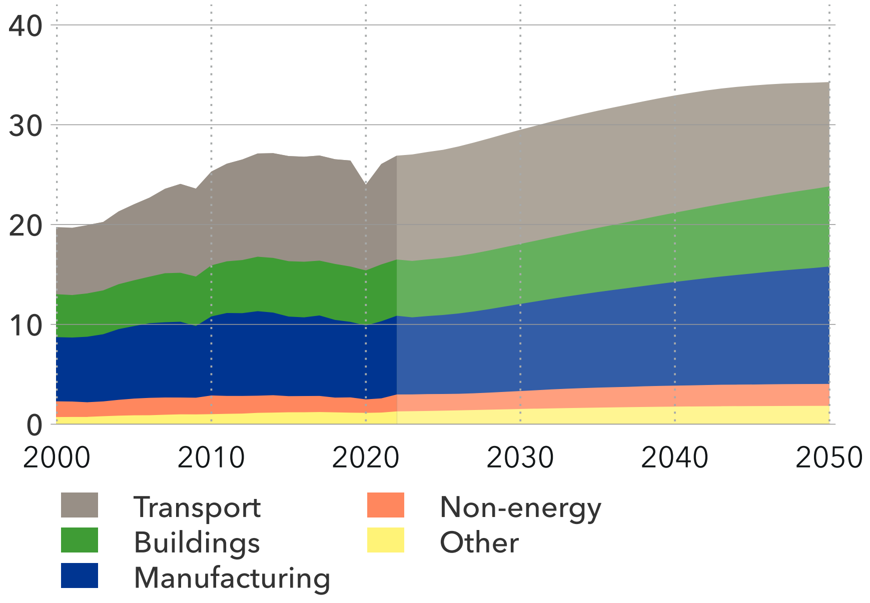


Historical data source: IEA WEB (2024)

FIGURE 8.2.3

Latin America final energy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2024)

Renewables: the workhorse of regional energy transition

Today, renewables already have a 63% share of power generation in Latin America, the highest among all the ETO regions. The largest renewable source is hydropower, supplying 41% of total power production.

There is substantial potential for growth of other renewable power sources in the region, which is already reflected in recent investment in new capacity. Given the favourable conditions in different parts of the Latin America region, countries such as Chile, Argentina and, to some extent, Brazil are investing in solar power to decarbonize energy and other sectors. Almost all of Latin America's coastline features conditions conducive to wind power and we foresee that onshore wind will increase its share from 9% to 26%; there will also be a small additional contribution from offshore wind at to 2% to 3% by 2050.

With these developments, the increasing demand for electricity will be met by solar and wind. We forecast that solar and wind will grow significantly in the coming decades to provide 44% and 29% of the electricity by 2050. The extremely robust growth in solar is due to the development of solar+storage that helps solar cover more hours when the sun is not shining. This alone will provide 12% of the electricity generation by 2050 (Figure 8.2.4).

At the same time, hydropower will increase 25% in absolute terms. Nevertheless, will decline to its share in the energy mix to 23% in mid-century as the other renewables grow so much more.

Biomass, in the form of liquid biofuels in transport, as a gaseous energy carrier substituting natural gas – and as solid biomass in the buildings sector – will cover 16% in the primary energy mix towards 2050 and will also be an important piece in the puzzle to support Latin America's energy transition.

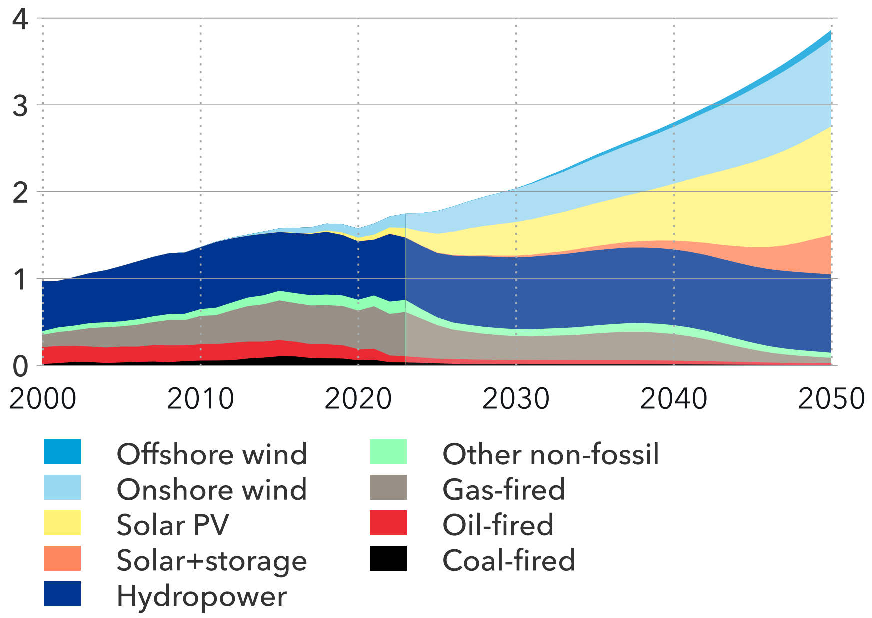
The increasing role of renewables in power will be accompanied by a corresponding decline in the share of fossil fuels from 32% currently to only 3% in 2050. The eradication of fossil fuels in electricity generation accelerates as solar+storage increases its impact.

There are, however, challenges associated with increase generation from renewables. The major one, and common to other regions, is a lack of adequate transmission infrastructure required to transport new generation. Currently, the lack of this infrastructure leads to bottlenecks and slows down the build-up of renewable capacity. For places like northern Chile, Argentina, and Panama, it is common for lack of transmission to cause electricity prices to reach zero at certain nodes of the respective electricity markets, which has negative financial impact on generators. While our forecast foresees doubling of power line capacity in the region, various storage solutions will be required to provide much-needed grid stability. Utility scale storage energy capacity will grow from a negligible 15 GWh presently to 2236 GWh by 2050, with Li-ion with utility scale solar comprising 27% and standalone Li-ion 15% of the storage capacity mix.

FIGURE 8.2.4

Latin America grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

Biofuels: reducing the dependency on fossils

Latin America has great potential to further displace imported fuels domestically with biofuels like bioethanol, biodiesel, and biogas/biomethane.

Brazil's sugarcane ethanol, Argentina's soya biodiesel, and Colombian palm oil biodiesel are prime examples of the region's success in providing renewable alternatives to fossil fuels. Latin American countries promote biofuel use through strong mandates (Zancaner, 2024), as for example Brazil being the pioneer with increasingly demanding blend interval of ethanol in gasoline (expected 30% by 2030) and biofuel rate in diesel (20% by 2030). Our results suggest the increased use of biofuel will contribute to a 20% increase in biomass use in Latin America. The export potential for these products risks being limited, however, as customers will require sustainability criteria with which it could be difficult to document compliance, one example being the EUs *RED-III* requirements.

More specifically, in aviation we expect the share of biomass to grow from almost nothing to 20% of the energy mix by 2050. This growth reflects strong focus on biofuels taken by countries such as Brazil, whose *New Industrial Policy* (2024) aims for 50% in the transport energy mix by 2033, and the *Fuel of the Future programme* (2023) targets to increase ethanol and biodiesel blends to 2030 and reduce aviation emissions by 10% by 2037.

The region is well-positioned for a global role in production of biomass-based energy. However, to mitigate environmental impacts associated with first-generation biofuels derived from food crops, Latin American countries should prioritize developing second- and third-generation biofuels, which utilize non-food biomass and waste materials as feedstocks. These advanced biofuels have a smaller environmental footprint and avoid direct competition with food production. Second- and third-generation biofuels have already been the focus of long-standing programmes in Brazil but are also gaining traction in other countries of the region, including Argentina, Mexico, Colombia, Chile, and Costa Rica (Advanced BioFuels USA, 2024).

Demand for methane as an energy carrier will start before 2030 and equal the demand for methanol as a feedstock by 2050. Similarly, the demand for ammonia as an energy carrier will outpace the demand for it as a feedstock.

Hydrogen: unrealized potential?

While strong electrification through solar and wind power growth is the main driver of the region's energy transition, Latin American countries are also investing thoroughly in renewable hydrogen. Today, Latin America produces only about 5% of the world's hydrogen output, almost entirely from unabated fossil fuels, for the region's manufacturing sector. Thanks to its abundant renewable resources, the region has an opportunity to develop renewable-based routes of hydrogen production. Individual countries in the region have continuously considered this pathway with an emphasis on potentially becoming an exporter of hydrogen to Europe, North America, and Asia. Our forecast suggests that, while the potential is there, given the current policy and project developments in the region and relative to the rest of the world, realizing this potential will be limited.

From the early 2030s, hydrogen produced by electrolysis powered by dedicated renewables will start taking off more rapidly, reaching around 59% of total hydrogen production in 2050. This share is dramatically higher than today but will comprise only about 6% of global hydrogen production through electrolysis, leaving the region lagging behind North America, China, Europe, and the Middle East and North Africa, but on par with OECD Pacific. Unabated fossil fuels will comprise only 18% of hydrogen production in Latin America by 2050, a dramatic decline from its 98% share in total regional production today. The remaining 23% will come from fossil fuels abated with CCS, predominantly through methane reforming processes.

Thanks to high-capacity factors, Latin America will be among the regions with the lowest levelized cost for solar-powered hydrogen production. In fact, the region's solar-based hydrogen is cheaper than most of its competitors, such as wind-based hydrogen (Figure 8.2.5). By 2050, the cost of solar-based hydrogen production in the region will decrease by more than 50% towards just around USD 2/kg, making this production process more competitive with natural gas-based production. From the late 2040s on, wind-based hydrogen production will remain slightly costlier than solar-based on average in the region. At promising wind sites, however, the levelized cost of hydrogen might be even lower than for solar-based hydrogen.

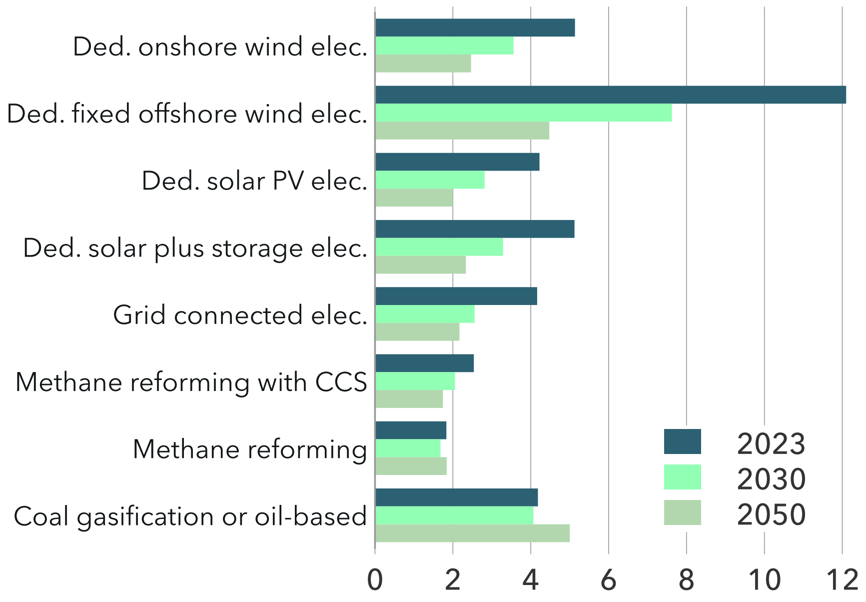
Given the low levelized cost of hydrogen production, and the vast potential for solar power exploitation as well as promising wind resources, Latin America will indeed contribute to global hydrogen exports. However, this contribution will be modest. By 2050, the region will comprise only about 5% of all hydrogen and derivatives traded globally; most of this will be ammonia for energy, and most of that delivered to North America by ships. In fact, almost 50% of North America's ammonia imports for energy purposes and almost all ammonia imports for feedstock will come from Latin America. Exports to Europe will be very limited and mainly comprise of hydrogen transported by sea.

Despite having potential for substantial renewable hydrogen uptake and clear intentions to pursue this route of energy transition, Latin American governments still need to establish frameworks, similar to those in Europe, North America, and OECD Pacific, to enable hydrogen production, export, and potential domestic use. Although the local costs of hydrogen production are at the lower range, Latin America's aspirations to become a renewable hydrogen exporter will be challenged by other regions where production costs are also low, but where stronger support for hydrogen production is already in place, such as North America and the Middle East and North Africa. In addition, while demand for hydrogen in Europe and North America will increase, fuelled by their hydrogen policies, their production will be increasing as well. Even more importantly, the requirements for emission intensity of hydrogen along the entire supply chain in Europe, North America, and OECD Pacific are getting stricter, which makes it more difficult for Latin America to rely on exports to these regions as the primary pull for their hydrogen production. Lastly, to realize its exports ambition, the region must properly plan the challenging part of this undertaking: hydrogen transport. This includes pipelines for intraregional distribution of hydrogen, and export terminals for hydrogen conversion to ammonia.

FIGURE 8.2.5

Latin America levelized cost of hydrogen production

Units: USD/kgH_2



Ded. = dedicated; elec. = electrolysis

> Thanks to high capacity factors, Latin America will be among the regions with the lowest levelized cost for solar-powered hydrogen production.

Progress in emissions reductions: too easy a target?
The region's average carbon-price level is projected to increase to USD 10/tCO_2 in 2030 and USD 40/tCO_2 by 2050. There are carbon-pricing schemes taxation in Argentina, Chile, Colombia, and in some Mexican states. Pricing is presently low, but additional pricing instruments are under consideration, such as in Brazil (see Section 6.3). Higher carbon pricing could also come about with stricter policies to comply with carbon-border adjustment mechanisms from large trading partners such as China and Europe, both of which have carbon pricing in place and are seen as possible trade partners for low-carbon hydrogen and other products.

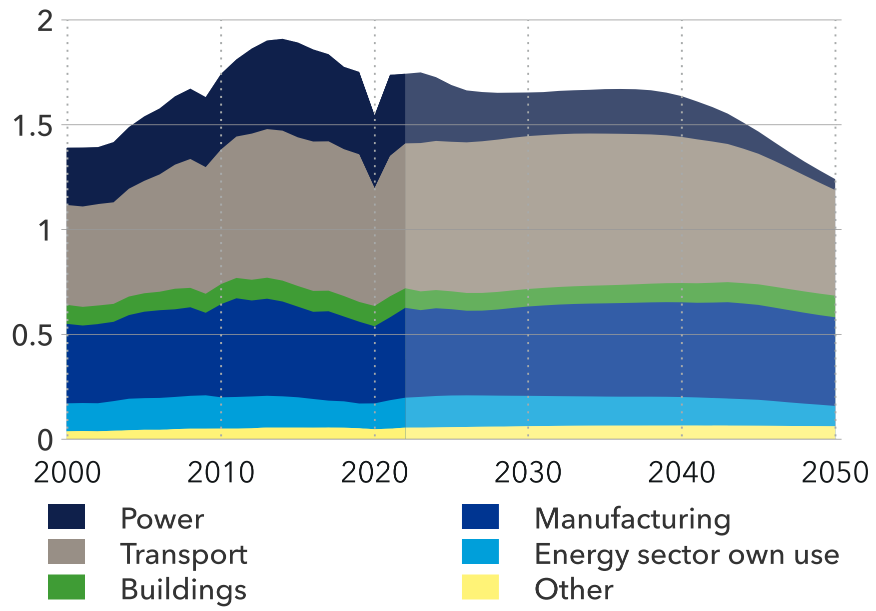
The efforts towards setting effective carbon pricing in the Latin America region are complicated by societal issues, such as inequality, poverty and political instability. The region has some of the highest levels of economic inequality in the world. Therefore, many governments in Latin America prioritize economic growth and poverty, reduction over climate policies. Countries like Venezuela, Brazil, and Mexico are heavily reliant on fossil fuel extraction for budget revenue; carbon pricing in these countries would necessitate significant and often politically sensitive energy sector reforms. Carbon pricing is further complicated by fossil fuel subsidies, which are ubiquitous in the region.

Latin America's energy-related CO_2 emissions peaked around 2015. They will decline further through the 2020s, stabilize in the 2030s, then decrease by 33% from 2023 levels to 2050, reaching slightly above 1 $GtCO_2$/yr (net of DAC), and 1.24 $GtCO_2$/yr if including industrial process emissions (Figure 8.2.6). The decline will be more pronounced in transport and manufacturing, driven by efficiency gains, a changing energy mix, and, to a smaller extent, carbon capture. Today and in the future, oil is the biggest contributor to emissions (65% by 2050) and is mainly used in Latin America's transport sector. The natural-gas dominated manufacturing and buildings sectors together will contribute almost a third to Latin America's emissions in 2050. By then, CCS will reduce CO_2 emissions by 42 Mt/yr, equivalent to around 4% of the region's emissions by mid-century. More specifically, a legislative framework is emerging in Brazil which will set the foundation for the application of CCS across multiple sectors, including the industrial sector (Chyzh, 2024). Additionally, these energy-related CO_2 emissions captured with CCS in the region comprise about 3% of global captured emissions. The role of CCS, while overall small in the region, will play an important role in the decarbonization of its oil producing countries.

FIGURE 8.2.6

Latin America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Historical data source: IEA WEB (2024)

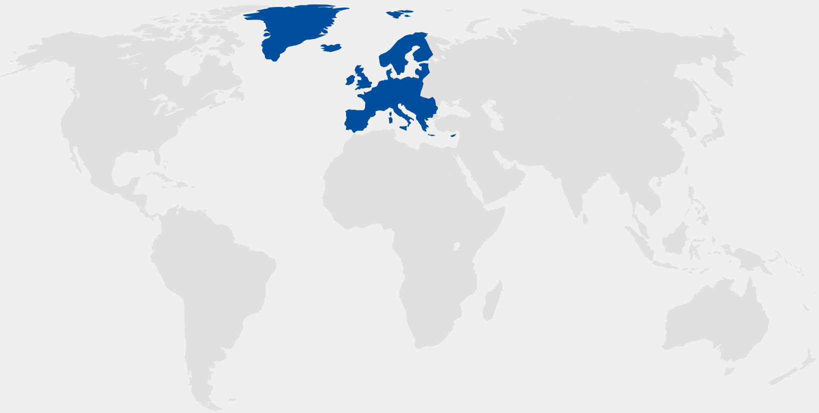
In the context of global climate policy, country NDC pledges indicate an increase in the regional target of limiting increases in emissions to about 65% by 2030, relative to 1990. Brazil updated its NDC in 2023, reverting to their original targets with the new government. Our Outlook shows energy-related emissions rising around 63% over the same 40-year period, suggesting that the regional target will be achieved by a small margin.

It should be noted that there are uncertainties in comparing targets and forecasts. Some countries are unclear about whether targets in NDCs also include non-energy related CO_2 emissions. In Latin America in particular, there is a large difference between targets including and excluding AFOLU (agriculture, forestry, and other land uses) due to the influence of the rainforest on the total emissions.

Latin America's 1.4 tCO_2 per person emissions in 2050 are 40% lower than today and in 2050 will be on a par with India and South East Asia. Some Latin American countries – including Brazil, Argentina, Colombia, and Chile – have indicated or already adopted carbon-neutrality targets by 2050. However, these targets often take into account the land and forestry sector, which means CO_2 uptake from rainforest areas are included.

8.3 EUROPE (EUR)

This region comprises all European countries, including the Baltics, but excluding Russia, all the other former Soviet Union Republics, and Turkey.



Austria, Belgium, the Czech Republic, Finland, France, Germany, Italy, the Netherlands, Norway, Poland, Spain, Sweden, and the UK account for **80%** of region energy use.

	Population (Million)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/ person (tonnes)
2023	544	29.1 53 400	68 125.5	3 5.6
2050	542	39.9 73 700	56.1 103.5	0.6 1.1

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.3 EUROPE (EUR)

Current position

Europe has a long history of supranationalism with joint EU commitments under the *Kyoto Protocol,* the *Paris Agreement*, and common energy, climate, and industrial policies advancing energy security, sustainability, market integration and, most recently, fast-tracking the clean energy transition.

The region has close intra-regional energy cooperation. Norway is part of the European Economic Area, the UK exports gas and electricity to the EU market, and there are energy infrastructure interconnections.

EU reliance on energy imports remains high with a dependency rate close to 60%. Through sanctions and the ambition to have zero dependence on Russian natural gas by 2027, fossil-fuel imports from Russia have plunged. LNG imports have increased with EU diversification efforts boosting supplies from the Middle East and North Africa and North America.

Fossil fuels accounted for 70% of EU primary energy supply, and renewables 23% of energy consumption, in 2022 (EEA, 2024). The electricity mix has steadily greened: EU power production was 74% emissions-free during January to June 2024 (Eurelectric, 2024).

With a stable population, energy demand has peaked and EU GHG emissions fell nearly a third (32.5%) between 1990 and 2022. Between the 55% reduction (by 2030) and climate-neutrality (by 2050) targets, the European Commission recommends a 90% reduction by 2040. Norway participates in EU climate legislation (2021–2030). The UK targets 68% emission cuts by 2030 and 77% for 2035.

Climate-related events between 1980 and 2022 caused economic losses of EUR 650bn in the EU with EUR 52.3bn in 2022 alone (EEA, 2023). A recent flooding event in Germany (May 2024) caused losses of EUR 4.5bn (Munich RE, 2024).

Pointers to the future

– Energy source diversification and the energy efficiency-first principle will remain cornerstones in European policy.

– Revised *National energy and climate plans* (NECPs) for 2021–2030 need strengthening as they fall short of EU *Green Deal* objectives (EC, 2023). In the UK, only around a third of emission cuts required for 2030 targets are covered by credible plans (CCC, 2024).

– Support is expected for the commercialization phase of critical technologies and infrastructure projects – offshore grids, hydrogen, CCS.

– The *Renewable Energy Directive* (RED III) raises renewable electricity penetration, but national implementations, especially RFNBO obligations on demand sectors (industry and transport) will need boosting.

– For renewable hydrogen, higher price levels in European Hydrogen Bank and national auctions are expected in the short-to mid-term given additionality requirements, free emissions trading system (ETS) allowance phase-down, and the most competitive projects being picked first. To put the 20MtH$_2$/yr supply target within reach, and as per audit recommendations (ECA, 2024), country efforts (targets, funding, permitting) will be firmed up alongside further clarity on EU funding arrangements for industry players.

– The EU's 50 MtCO$_2$/yr storage target by 2030 confirms CCS's role. Continued support includes EU Projects of Common Interest (PCIs), government funding nationally, and broader adoption of OPEX payments (carbon CfDs with sale of CO$_2$ at guaranteed prices) beyond pioneers (France, Germany, the Netherlands, and the UK) to de-risk industrial decarbonization.

– Key post-2030 policy framework concerns will be industrial competitiveness and progressing aims kickstarted in the *Critical Raw Material Act* and *Net-Zero Industrial Act* to reshore strategic sectors/manufacturing. To this end, relaxed *State Aid* rules beyond 2025 are likely.

Europe at the energy-industry crossroads

Since Russia invaded Ukraine and Russian natural gas imports to Europe abruptly stopped, Europe is coming to realize that relying solely on rules-based globalization and free trade for prosperity is not enough to maintain security and resilience. Greater geopolitical polarization and nations competing to dominate key economic sectors (e.g. clean energy technologies, AI, IT, and critical raw materials) suggest a Europe becoming increasingly isolated and vulnerable – caught between, at best, lukewarm allies and, at worst, potential aggressors (Macron, 2024; Wertheim, 2024).

Hard work will pay off

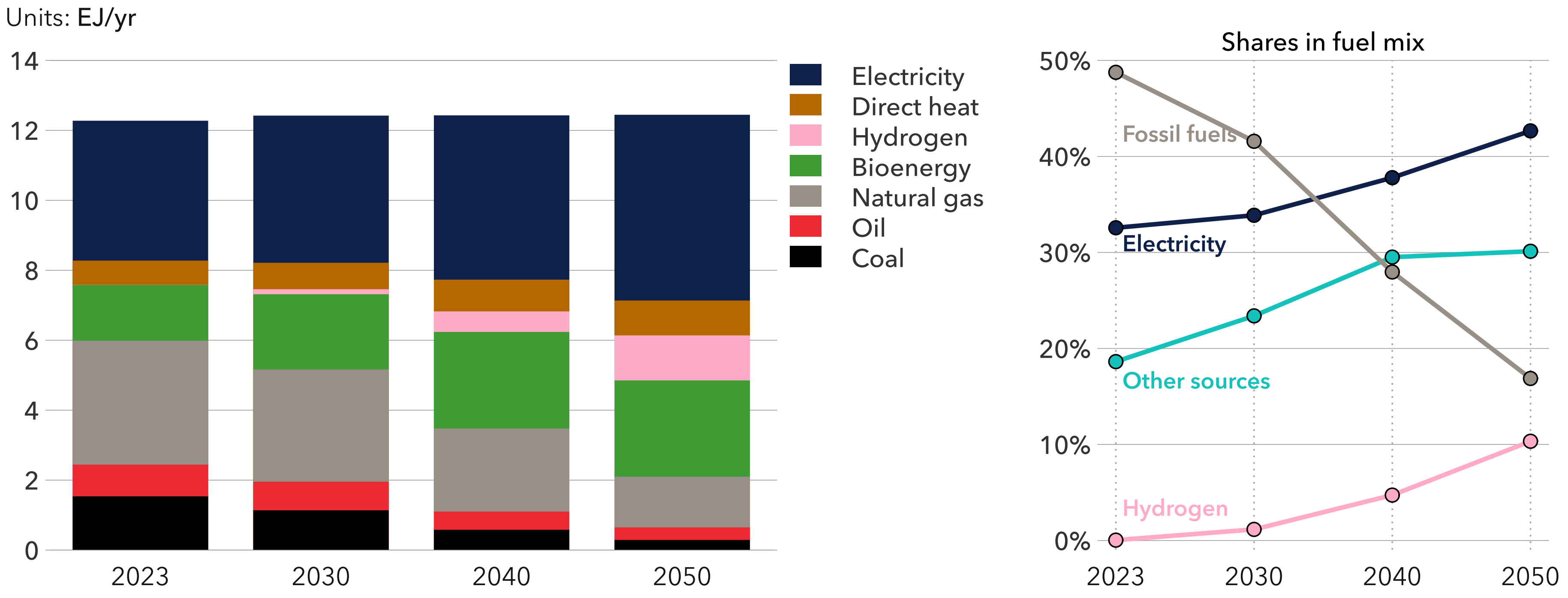
In the two years since Russia's invasion of Ukraine, Europe has taken significant actions to address these challenges and maintain its position as a leading technology manufacturer, particularly in industries like automotive and high-end electronics. To safeguard economic competitiveness while adopting stringent environmental policies, various measures and regulations have been implemented. Among these is the *Carbon Border Adjustment Mechanism* (CBAM) (EC, 2024a), designed to level the playing field against non-EU countries with less rigorous GHG regulations. Another key regulation is the *Net Zero Industry Act* (NZIA) (European Union, 2024), a component of the *European Green Deal* (CircuLaw, 2024), which aims to bolster the resilience and competitiveness of key industries in net-zero technologies.

In 2022 and 2023, European manufacturing energy demand declined from the post-COVID rebound levels of 2021, largely due to high energy prices resulting from geopolitical events. The industrial sector in Europe reduced its output during these years because of these elevated prices. However, we expect this reduction to be temporary. Driven by the comprehensive *European Green Deal* (European Commission, 2024b) and the NZIA, manufacturing energy demand is expected to increase slightly in 2024 and then remain relatively stable at approximately 12.5 EJ/yr until 2050 (Figure 8.3.1). We project this stability despite expected GDP growth and a slight increase in the secondary sector's share of GDP over the period.

While the overall energy demand in manufacturing remains constant from 2023 to 2050, there is a significant shift in the types of energy carriers used. By the early 2030s, we project that electricity's share of manufacturing energy demand will surpass the combined share of fossil fuels (coal, oil, and natural gas) in Europe. In 2023, natural gas accounted for 30% of the sector's energy demand, but we forecast this will decrease to 12% by 2050. In contrast, electricity's share will rise to 43%, with hydrogen accounting for 10%. This transition away from natural gas began in earnest in 2022, spurred by the loss of easy and cheap access to Russian natural gas. Another instigator of the move away from fossil fuel is the EU *Renewable Energy Directive* (RED III) (EU, 2023) which sets binding targets for increasing renewable energy in energy sectors, crucially also including manufacturing energy use. Additionally, EU-wide carbon pricing, the CBAM, and carbon contract-for-difference (CCfD) types of mechanisms (Climate Friendly Materials Platform, 2020) will further incentivize European manufacturers to move away from carbon-intensive energy carriers.

FIGURE 8.3.1

European manufacturing energy demand



The *European Green Deal* has other measures to boost decarbonization of the energy sector and the wider economy. They include, among others, simplifying the regulatory environment, especially with leaner permitting of renewable energy; faster access to funding for green innovation; and access and frameworks for skills and training to attain a climate-neutral economy.

> A cornerstone of Europe's industrial competitiveness and climate leadership will be the effective electrification of end-use sectors, alongside hydrogen and carbon capture.

Greener steelmaking is a cast-iron certainty

The energy transition in manufacturing is particularly evident in iron and steel, which is also included in the EU's CBAM. Coal use in blast oxygen furnaces (BOF) has gradually declined since the 1990s due to improved energy efficiency in steelmaking. Starting in the 2010s, there has also been a notable increase in using electric arc furnaces (EAF) to melt scrap steel for crude steel production in Europe (Figure 8.3.2). This shift has contributed to reduced demand for coal, increased demand for electricity, and sustained demand for natural gas.

We anticipate that, starting in the mid-2030s, there will be a next wave to replace European BOFs with steel produced using direct reduced iron (DRI) via electric arc furnace technology (Figure 8.3.2). This transition can be achieved using hydrogen as both an energy source and a reducing agent. By mid-century, we expect Europe's iron and steel industry to require nearly 450 PJ/year of hydrogen, accounting for 35% of the total energy demand for crude steel production.

A cornerstone of Europe's industrial competitiveness and climate leadership will be the effective electrification of end-use sectors, alongside the use of hydrogen and carbon capture technologies for hard-to-abate sectors and emissions. This is illustrated in Figure 8.3.3, which presents the final energy demand of Europe by energy carrier.

Fossils falling

By 2046, we expect electricity to overtake fossil fuel as the leading energy carrier meeting final energy demand in Europe (Figure 8.3.3). Combined with an almost fully decarbonized power grid, this would see fossil fuels meeting only a third, and electricity a half, of the total energy demand in mid-century. Hydrogen will meet a small but important 6% of the final energy demand, especially in heavy industries in order to provide high-temperature heat, thus supporting the continued competitiveness of European industries while simultaneously decarbonizing them. Hydrogen will be crucial for providing high-temperature heat in manufacturing process without any end-use CO_2 emissions.

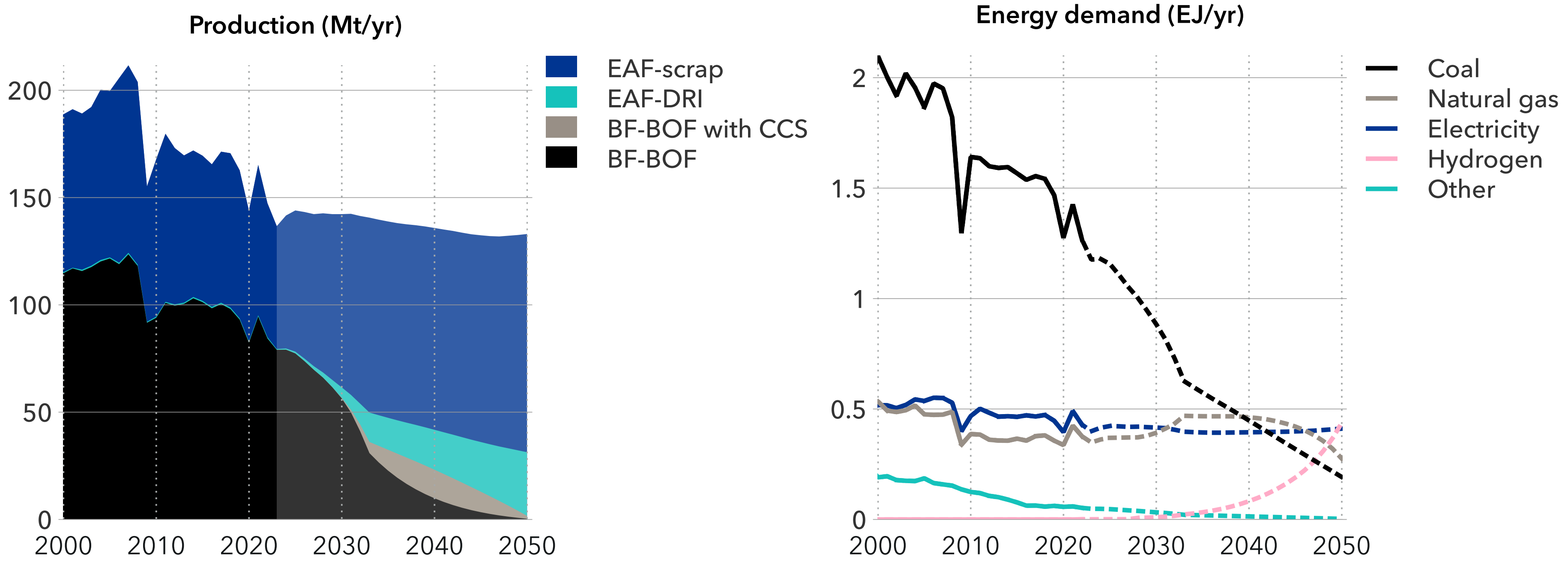
Most coal used in Europe in 2023 is for power generation, with coal's share in final energy demand reflecting its use in the manufacturing sector. In the next two decades, policy goals to increase renewables' share in energy and increasing carbon prices lead to coal becoming prohibitively expensive in Europe. This points to a likely phase-out of coal in final energy demand.

Most oil used in Europe is for the transport sector. With increasing electrification of road transport, oil's share in final energy demand reduces drastically from 42% in 2023 to just 18% by 2050.

Most natural gas used in Europe is for buildings, predominantly for space and water heating and for

FIGURE 8.3.2

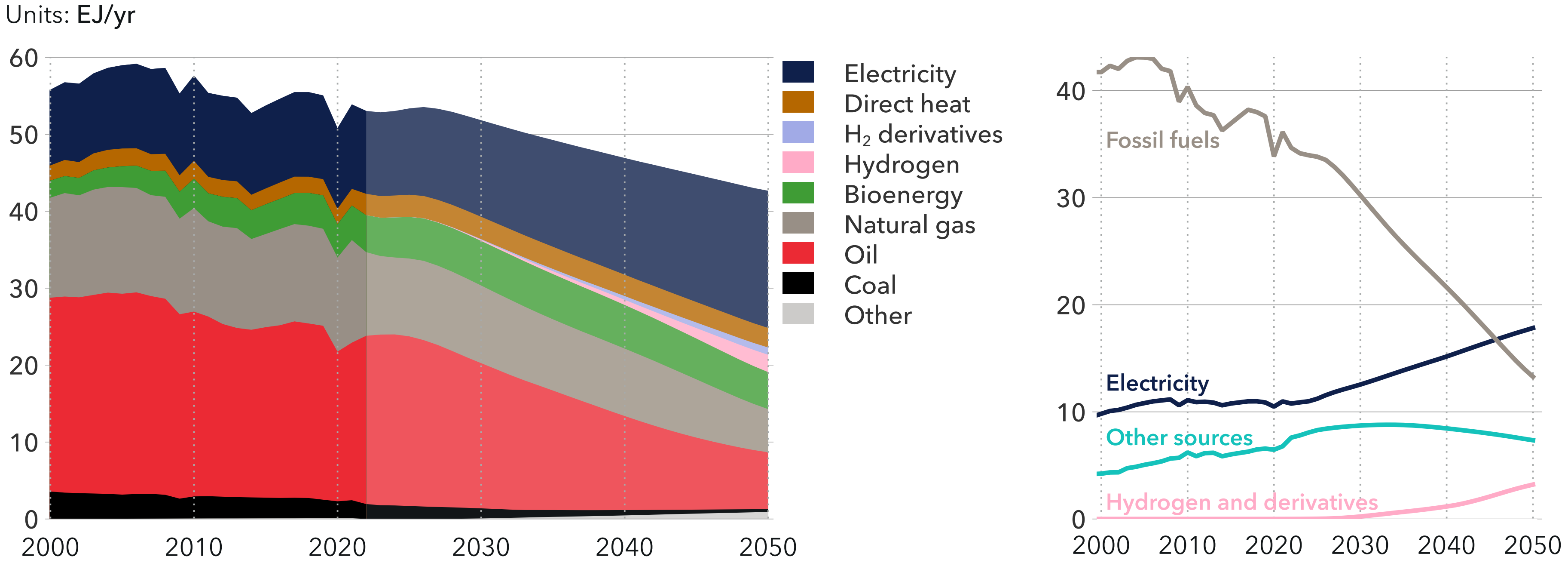
Iron and steel production and energy demand in Europe



EAF: Electric Arc Furnace; DRI: Direct Reduced Iron; BF-BOF: Blast Furnace-Basic Oxygen Furnace. Historical data source: World Steel (2024), IEA WEB (2024)

FIGURE 8.3.3

Europe final energy demand by carrier



Historical data source: IEA WEB (2024)

power generation. With the adoption of EU ETS for power plants in 2005, the phase-out of coal corresponded to installation and running of gas-fired power plants. However, with the cessation of easy access to natural gas and high natural gas prices in 2022 and 2023, electrification of space and water heating is well underway in Europe.

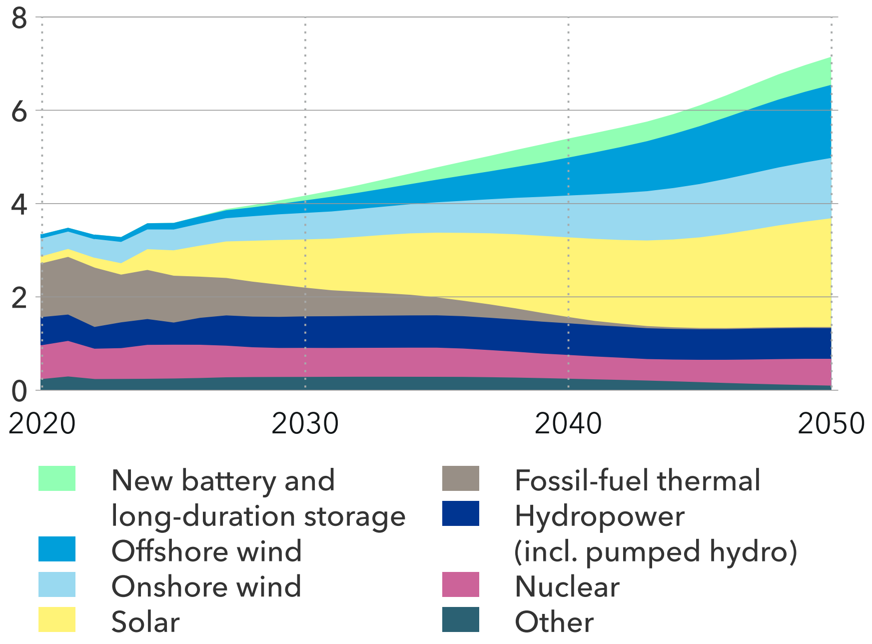
Going electric

With electricity's expected prominent role in the energy transition, a more detailed look at the transition within the power sector is necessary. Figure 8.3.4 shows Europe's past, present, and forecast future electricity supply from 2020 to 2050. Increasing electrification of demand sectors leads to annual electricity supply increasing from 3.3 PWh/yr in 2023 to 7.2 PWh/yr by mid-century, a 3% year-on-year growth from 2023 to 2050. This alone signifies the deep transition at the heart of the European energy sector; while final energy demand reduces year-on-year, deepening electrification brings with it year-on-year growth of electricity demand.

FIGURE 8.3.4

Europe electricity supply by generation type

Units: PWh/yr



Along with this increase in electricity supply, we expect Europe to completely phase out fossil-fuel based thermal power generation over the next 18 years. To compensate for this, power supply from solar and offshore wind will ramp up. The rise in renewables will be aided by region-wide decarbonization goals, carbon pricing, the *REPowerEU* plan targeting a 69% renewable energy share in 2030 (EU, 2023), and the EU electricity market design rules which allow future support through two-way CfDs. There is policy support for utilities to incorporate renewables in their generation mixes. Solar and offshore wind will overtake the current renewable power leaders, hydropower and onshore wind.

Hydropower supplied 16% of Europe's electricity in 2023. In absolute terms, hydropower supply remains the same from now to 2050, while its share in total supply will reduce due to the forecast strong demand growth and corresponding ramp-up of solar and offshore wind. More importantly, we forecast that Europe will meet its 69% renewable electricity target and that this share will increase to 91% by 2050.

We forecast growth in power supply from both bottom-fixed and floating offshore wind, rising from a combined 104 TWh/yr in 2023 to 1,600 TWh/yr by mid-century. The wind resources in the North Sea and the English Channel aid in this regard. Similarly, electricity supply from solar panels, standalone or co-located with Li-ion batteries, grows from 245 TWh/yr in 2023 to 2,400 TWh/yr by 2050, outpacing total electricity demand growth. This trend in solar is already well underway in European regions of high solar irradiation, such as Spain and Portugal, but also in more northern markets like Sweden.

Price of power

Such a strong supply growth is possible because of capacity build-out of solar PV and wind power plants, especially when it replaces the retiring and phased-out or ageing coal, natural gas, and nuclear capacity. However, building capacity is an economic decision usually based on the levelized cost of electricity (LCOE) of the different power plant types.

Figure 8.3.5 illustrates the LCOE of selected types of power plants in Europe from 2020 to 2030. The values are given for the years when the final investment decision was or is to be made. Within the period, solar PV – both standalone and co-located with Li-ion battery storage – has the lowest LCOE in Europe, along with onshore wind.

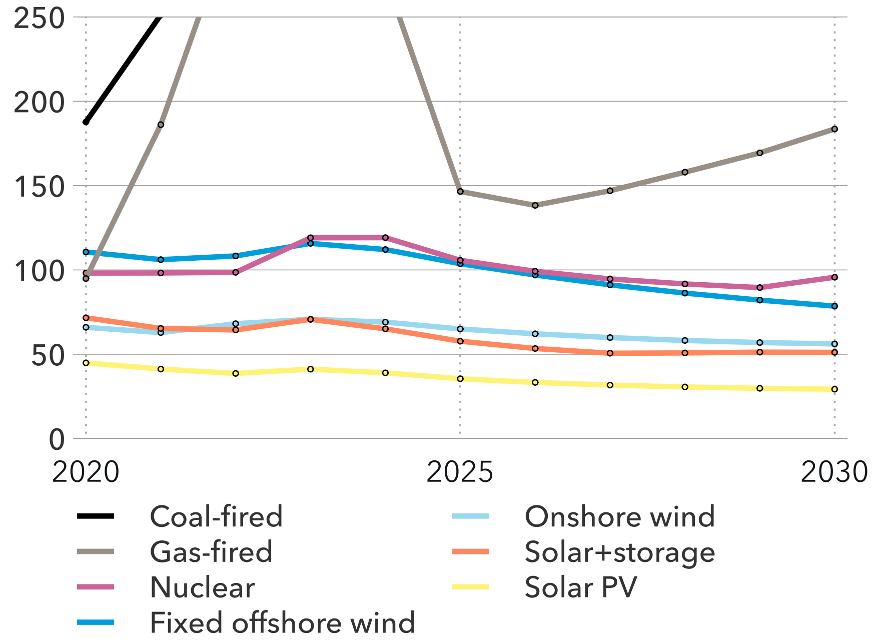
From 2023, reductions in CAPEX and other fixed costs due to the learning-by-doing effect also bring the LCOE of fixed offshore wind below that of conventional nuclear power for Europe. These LCOE calculations illustrate why the installed capacity of both solar and offshore wind grows in Europe in the coming decade. Their shares of the power supply grow as well.

To improve the lucidity of Figure 8.3.5, the vertical axis is capped at US¢ 25 per kilowatt hour. In this graph, the LCOE of coal-fired power plants in Europe is visible only in 2020. After that, the carbon price and the cost of coal make the LCOE of a coal-fired power plant much higher than any other type, thus dissuading the installation of new coal-fired power capacity after 2020. The LCOE of natural gas-fired power plants increases markedly between 2021

FIGURE 8.3.5

Levelized cost of electricity of selected power plants types in Europe

Units: USD/MWh



and 2024 because of the high price of natural gas in those years and continues to rise from 2025 because of the associated carbon costs.

Strong growth in wind power is also driven by consolidation of the region's manufacturing and technological prowess in manufacturing wind turbine systems and by the EU ensuring that wind power plays an essential role in attaining its renewable energy target.

Learning from past mistakes

Europe is proactively taking steps to protect its wind turbine industry from facing the same challenges that led to the decline of its solar panel industry. Europe's solar industry, once thriving, lost its competitive edge to cheaper Asian manufacturers who benefited from lower labour costs and substantial government support aimed at dominating the global solar market. Now, Europe imports most of its solar PV panels and modules from Asia. Similar dynamics are emerging in the wind turbine market. There is now surplus production capacity in Greater China, driven by significant government investments in clean technology, and Chinese manufacturers can offer wind turbines at prices that make it very difficult for European manufacturers to compete.

To address market distortions that threaten European wind industry players, the EU has launched a *Wind Power Action Plan*. This includes measures such as anti-dumping and anti-subsidy regulations (Johansson, 2023) to protect European wind system manufacturers from unfair trade practices by foreign entities. Furthermore, we also observe that the levelized cost of electricity (LCOE) for fixed offshore wind diverged between Greater China and Europe from 2021 to 2024, despite the global cost-learning effect (Figure 8.3.6). We anticipate that the LCOE for fixed offshore wind in Europe will continue to be higher than in Greater China until 2030, due to supply-chain disruptions and increased capital costs.

Carbon under pressure

Another important aspect of the electricity supply in Europe is the use of CCS in the power sector. Figure 8.3.7 illustrates the role CCS is set to play in reducing emissions from thermal power plants in Europe in the future.

By 2050, we forecast that a fifth of the bioenergy-based electricity supply will come from plants capturing the CO_2 emitted. Similarly, little more than a quarter of the electricity supply from coal-fired power plants in Europe will come from plants with CCS by mid-century. While this is significant, it should be noted that the absolute amount of

FIGURE 8.3.6

Levelized cost of fixed offshore wind in Europe and Greater China

Units: USD/MWh

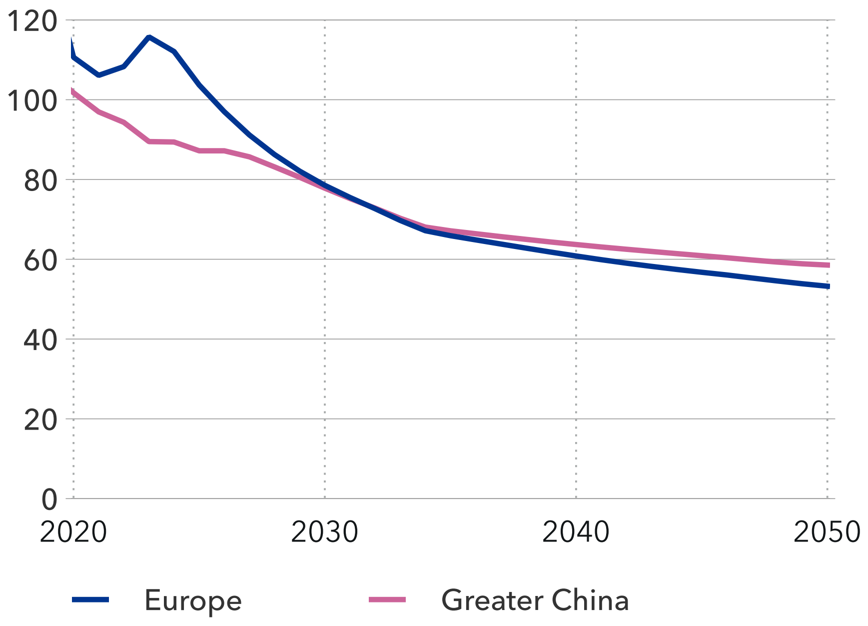
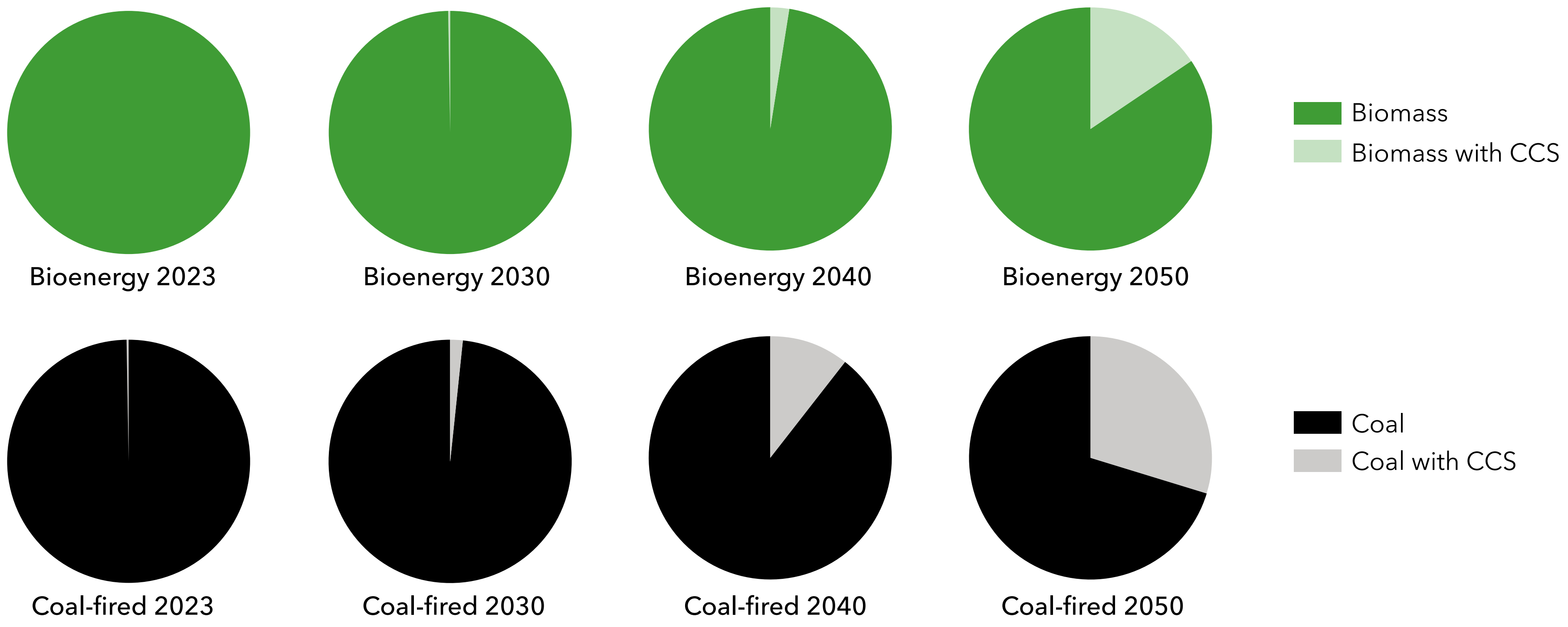


FIGURE 8.3.7

Carbon capture and storage in bioenergy and coal-fired power plants



electricity supplied by coal-fired power plants is minuscule by 2050. The majority of the emissions captured from bioenergy-based power plants are considered net-negative, thus providing an additional revenue stream for the power plant operators and increasing their feasibility and operability.

Three pathways for gas-fired power supply are shown in Figure 8.3.8: conventional methane, methane with CCS, and methane blended with hydrogen. In addition to combusting methane in a turbine, a significant portion of the electricity will be produced by blending hydrogen with methane. By mid-century, we forecast that half the electricity from gas-fired plants in Europe will be from methane with CCS, with hydrogen-fired turbines producing almost all the rest. It should be noted that the absolute amount of electricity produced from gas-fired turbines is very little, amounting to about 0.2% of total electricity generation in 2050. Nevertheless, hydrogen blended with natural gas amounts to about 2.6 Mt in 2050, 8% of total hydrogen demand in Europe (Figure 8.3.9).

Full carbon value-chain model driving CCS in Europe

CCS technologies are included in the EU's *Net Zero Industrial Act* (NZIA), adopted in May 2024 (EU, 2024). These are considered a vital part of decarbonizing the energy sector in Europe. To this effect, Europe's 2030 target for annual CO_2 injection capacity is 50 million tonnes, which we forecast it will anchieve. The regulation builds on work that identified potential value chains (JRC, 2024), a detailed and updated EU directive (EU, 2023), and includes requirements on big emitters with the aim of establishing full value chains from oil and gas production to permanent storage of carbon dioxide.

In parallel, EU member states are progressing national legislation and regulation to facilitate this implementation. One example is Germany, where a wider carbon management strategy (Clean Energy Wire, 2024) is reforming the existing carbon-storage law to allow for CCS.

FIGURE 8.3.8

Electricity supply from gas-fired power plants in Europe

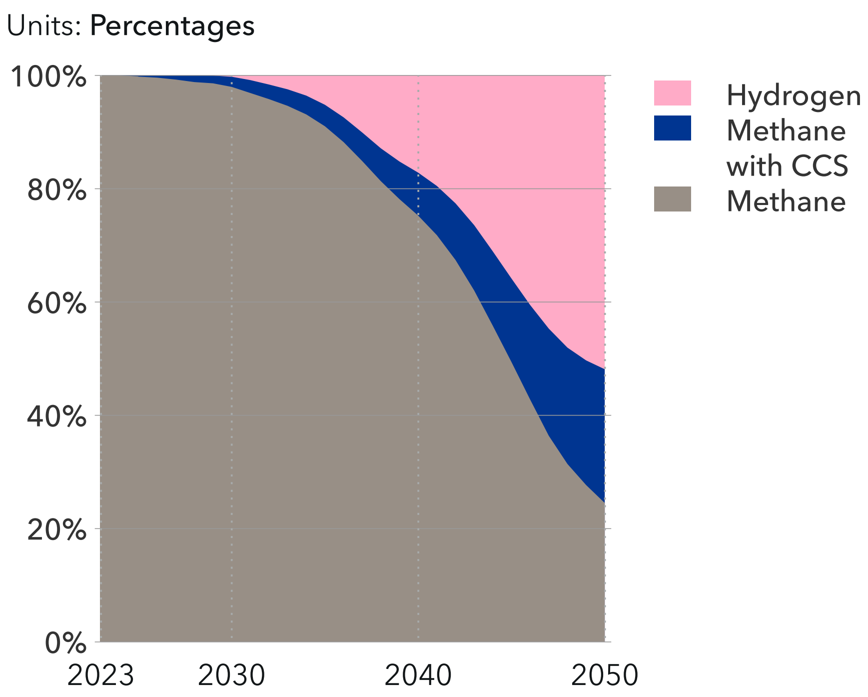
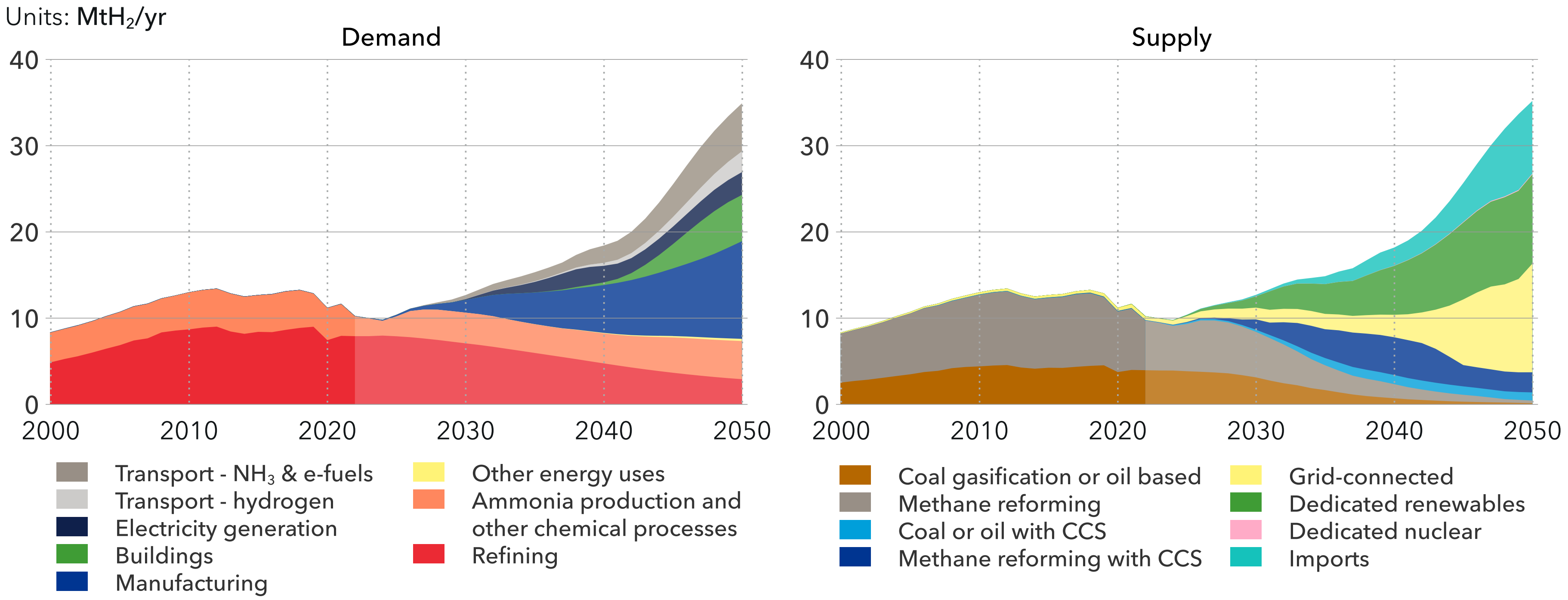


FIGURE 8.3.9

Europe hydrogen demand and supply



The NZIA-regulation mandates oil and gas producers to provide storage capacity according to their pro-rata shares of EU crude oil and natural gas production. The industry has quickly responded to this; by summer 2024, deals were already in place to implement full value chain storage sites with the inclusion of storage sites. Examples are:

- Offshore storage licences for the North Sea (Offshore Engineer, 2024)
- Onshore CO_2 storage in Denmark (Wass, 2024)
- French-Norwegian cooperation on CO_2 removal in the Dunkirk (Dunkerque) area to be stored under the seabed off Norway (PG Journal, 2024)
- A project in Norway is operational for storage from autumn 2024 with first deliveries planned for 2025 (Northern Lights, 2024)

Hydrogen as a transition building block

Hydrogen in Europe will play many roles in Europe's energy transition. It is a vital energy source for heavy industry and for continuing the use of peak-gas-fired power plants without relying on natural gas from external sources.

Figure 8.3.9 illustrates Europe's hydrogen supply sources and major demand categories. We forecast hydrogen demand to be 35 Mt/yr by mid-century, with a third (about 11.5 Mt/yr) being needed for the manufacturing sector. Two other major uses are as an energy carrier for buildings and as the raw material for producing ammonia and e-fuels for the transport sector. The current major demand segment for hydrogen, oil refining, will constitute only 8% of

Europe's total hydrogen demand in 2050, compared with 65% in 2023. As oil demand in Europe starts declining, the hydrogen needed for 'sweetening' the oil will also reduce proportionately.

Currently, most hydrogen is produced through steam methane reforming (SMR), and the rest through coal gasification. Looking to the future, policy mandates around the carbon content and conditions for hydrogen to be considered 'low-carbon' (3.38 kgCO$_2$-eq/kgH$_2$) and/or 'renewable' (e.g. electricity additionality requirements post-2028, temporal matching in 2030) aim to ensure that hydrogen is produced from renewable energy sources or achieves at least 70% GHG reduction compared to fossil-based hydrogen. Starting from 1 January 2028, the EU will require 'additionality', meaning renewable electricity powering hydrogen production must come from new capacity that would not exist in the absence of hydrogen/RFNBO production. Similarly, temporal matching intends to make sure that the electricity used to produce hydrogen does not come from the grid when fossil-fuels are setting the price at a particular hour and the electrolyser demand is not increasing fossil-fuel use in the grid.

These policy requirements, and the availability of near-zero marginal cost solar and wind electricity in the main grid, will lead to hydrogen production routes changing drastically. By 2050, we forecast that almost 40% of the hydrogen will be produced through electrolysers connected to the main grid. Cost-effective dedicated renewables, coupled with electrolysers, are the second largest producer of hydrogen in 2050.

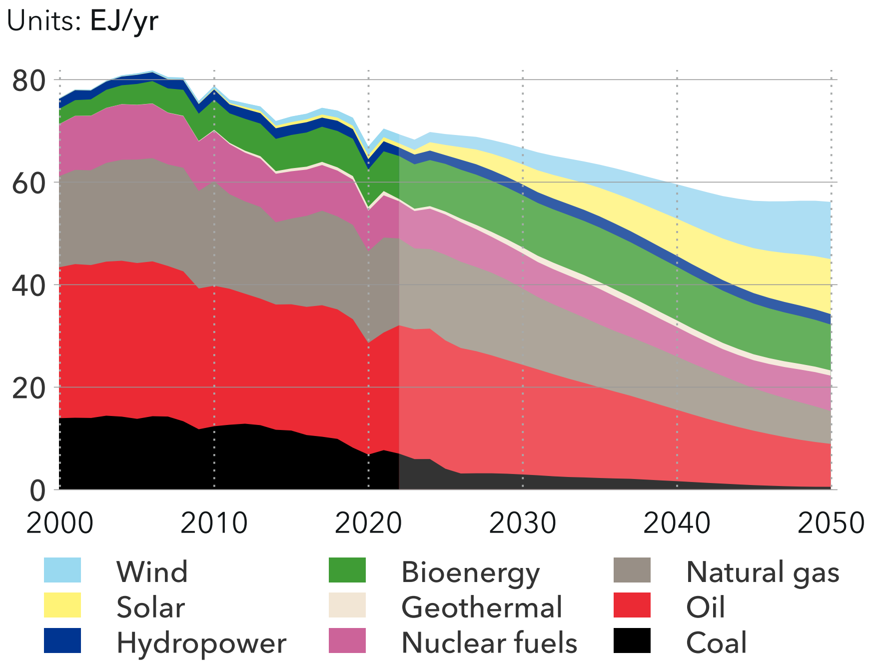
We also foresee that about a quarter of Europe's hydrogen supply would need to be imported in 2050, given the cost of producing hydrogen domestically.

Energy essentials

Based on the energy transition that we foresee, Figure 8.3.10 illustrates the past, present, and forecasted future to 2050 for primary energy consumption in Europe. From the 1990s to the late 2000s, Europe relied on coal to power its energy sector and economy. This started changing in the late 1990s with increasing use of natural gas and nuclear power. Going forward, the use of coal, oil, and natural gas in primary energy consumption will decline, while the shares of solar and wind will increase.

FIGURE 8.3.10

Europe primary energy consumption by source

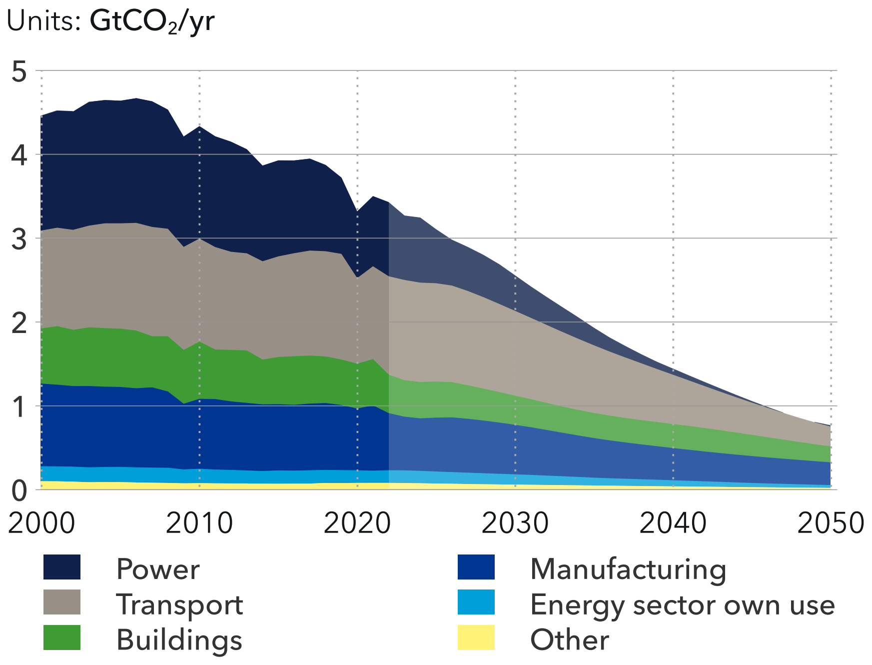


Historical data source: IEA WEB (2024)

In 2023, the share of renewables in primary energy consumption in Europe was 20% and has remained at that level since achieving the *Renewable Energy Directive* (2018/2001/EU) target. In our forecast, we expect the share of renewables in primary energy consumption to increase to 31% by 2030. This would fall just short of the previous minimum 32% target set for 2030, and would make it harder to reach the revised and increased target (2023) of a 42.5% share for renewables set out in the *Renewable Energy Directive* (RED III). In the longer term, we expect the share of renewables to rise to 60% in 2050, with fossil fuels having only a 27% share by then. The rest of primary energy consumption in mid-century will be met by nuclear energy.

FIGURE 8.3.11

Europe energy-related CO$_2$ emissions by sector



Historical data source: IEA WEB (2024)

As for GHG, the EU and UK commitments in NDCs aim for emission reductions of 55% and 68%, respectively, by 2030 compared to 1990 levels. Keeping in mind that our predictions exclude country-specific emissions, and that Europe's domain extends beyond the EU, our forecast suggests a 46% reduction in Europe's energy sector CO$_2$ emissions including industrial process emissions by 2030 from the 1990 benchmark. Concerning the 2040 interim target being debated in the EU, our forecast suggests a 71% emissions reduction by 2040. On the 2050 climate-neutrality goal by 2050, we forecast that Europe's CO$_2$ emissions, including energy sector and industrial process emissions, will have declined by 80% from 2023 levels (after CCS and DAC), resulting in annual emissions of 0.7 GtCO$_2$ (Figure 8.3.11). This indicates that Europe will not fully achieve the prevalent net-zero pledges among its nations.

In 2023, the sector with the most emissions in Europe was transport, with a share of 37%, followed by the power sector with 24%. By 2030, emissions from the power sector will almost halve, while those from transport remain more or less as now. By 2050, transport emissions will be a fifth of their level in 2023 thanks to deep electrification of road transport. Despite this reduction, transport will still account for a third of Europe's total remaining emissions in mid-century, reinforcing the difficulty of eliminating emissions from other transport modes such as maritime and aviation.

8.4 SUB-SAHARAN AFRICA (SSA)

This region consists of all African countries except Morocco, Algeria, Tunisia, Libya, and Egypt, which are included in the Middle East and North Africa region.

Nigeria, Ghana, Kenya, Tanzania, and South Africa account for **80%** of region energy use.

	Population (Billion)	GDP* (USD Trillion)	GDP/person (USD)	Energy use (EJ)	Energy use/person (GJ)	Energy-related CO_2 emissions (Gt)	Energy-related CO_2 emissions/person (tonnes)
2023	1.22	5.7	4 600	29.3	23.4	0.9	0.7
2050	2.14	24.5	11 400	47.5	22.2	1.4	0.6

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.4 SUB-SAHARAN AFRICA (SSA)

Current position

The region has abundant renewable resources and minerals essential for renewable power, energy technologies, and electrification. A fast-growing, resourceful young population is ready to drive change if enabled by vocation, skills, and capacity-building for clean-energy projects and sectors.

The African Union plays a unifying role through flagship projects and a common position on energy access and a just transition, stipulating deployment of all forms of renewable and non-renewable energy resources to address energy demand and development imperatives (AU, 2022), including natural gas as a transition fuel.

Bilateral donors and multilateral finance/development institutions, like the African Development Bank, finance energy investments. Concessional climate finance is rising but comes against an overall decline in official development assistance (IMF, 2023). *Just Energy Transition Partnerships* in South Africa and Senegal have support from the International Partners' Group (EIB, 2023). China's *Belt and Road Initiative* (BRI) has agreements with 44 countries in the region, generally investing in power, transport and infrastructure projects.

The green supply mix, 40% fossil fuel and 60% renewables (2023), has the caveat of energy-deficiency and a growth in the population without electricity access over three consecutive years (REN21, 2024) as energy-infrastructure developments lag behind needs. Population and urbanization are booming, pushing energy demand and emissions upwards, although some region countries have net-zero targets, e.g. South Africa by 2050 and Nigeria by 2060.

The region faces climate-change effects including record-breaking heat, precipitation anomalies, and severe flooding. As the frequency of extreme weather events increases, adaptation costs are estimated at USD 30 to 50bn each year over the next decade (WMO, 2024).

Pointers to the future

- Energy transition policy (see Table 6.4) seeks to tackle energy poverty, provide energy for industrialization and economic growth, and pave the way for clean energy and net-zero emissions.
- Renewable power targets are common, some for up to 100% renewables by 2030. South Africa's ambitions will likely accelerate, given election results and critique of the *Integrated Resource Plan 2023* (Meridian Economics, 2024). To attract private capital to the region, international public funding will play an important derisking role, including currency risks, to demonstrate procurement and 'first-of-a-kind' projects and create certainty for investors. Emerging road transport electrification policies lack incentive schemes and adequate infrastructure.
- Grid infrastructure buildout will be a focus area in concessional finance and private-public collaboration, such as the partnership between IRENA's Energy Transition Accelerator Financing (ETAF) platform and pan-African infrastructure investor Africa50, and the Alliance for Green Infrastructure in Africa.
- With global interest in resource endowments, a balance of local content requirements, domestic reform, and improved access to finance is needed to nurture domestic industries to capitalize on mineral wealth.
- Several countries pursue hydrogen/derivatives production: Kenya for 250 MW electrolyser capacity by 2032, Angola for 280 kt/yr ammonia, and Namibia for 12 Mt/yr by 2050 (Medinilla et al., 2024). The *South African Green Hydrogen Commercialization Strategy* funding needs (2023–2027) exceed USD 17bn (DTIC, 2023) and incentives are modest. Realizing hydrogen opportunities will depend on offtake in compliance markets such as the EU, international financing, and high-income regions' support schemes, such as the H2Global Foundation, the international part of EU's auction programme.

A unique region with diverse trajectories

A unique energy system

With an average annual increase of 34 million individuals (equivalent to the inhabitants of a medium-sized country), Sub-Saharan Africa's fast-growing population will reach 2.1 billion in 2050. Paired with a legitimate desire to develop its economy, the region will be decisive in global future energy demand and carbon emissions. There is some good news here for climate change mitigation. The energy transition has a unique shape in Sub-Saharan Africa compared with the rest of the world: the region's projected economic development will be realized with a decrease in emissions per capita, a feature that no other region has achieved so far.

Understanding our forecast requires looking at Sub-Saharan Africa's starting point in the energy transition. With more than 50 individual countries, and no real common energy strategy, the subcontinent can be seen as an energy archipelago, with varying of energy demand, population, and GDP per capita. Two countries stand out here: Nigeria and South Africa currently account for about half the region's energy demand.

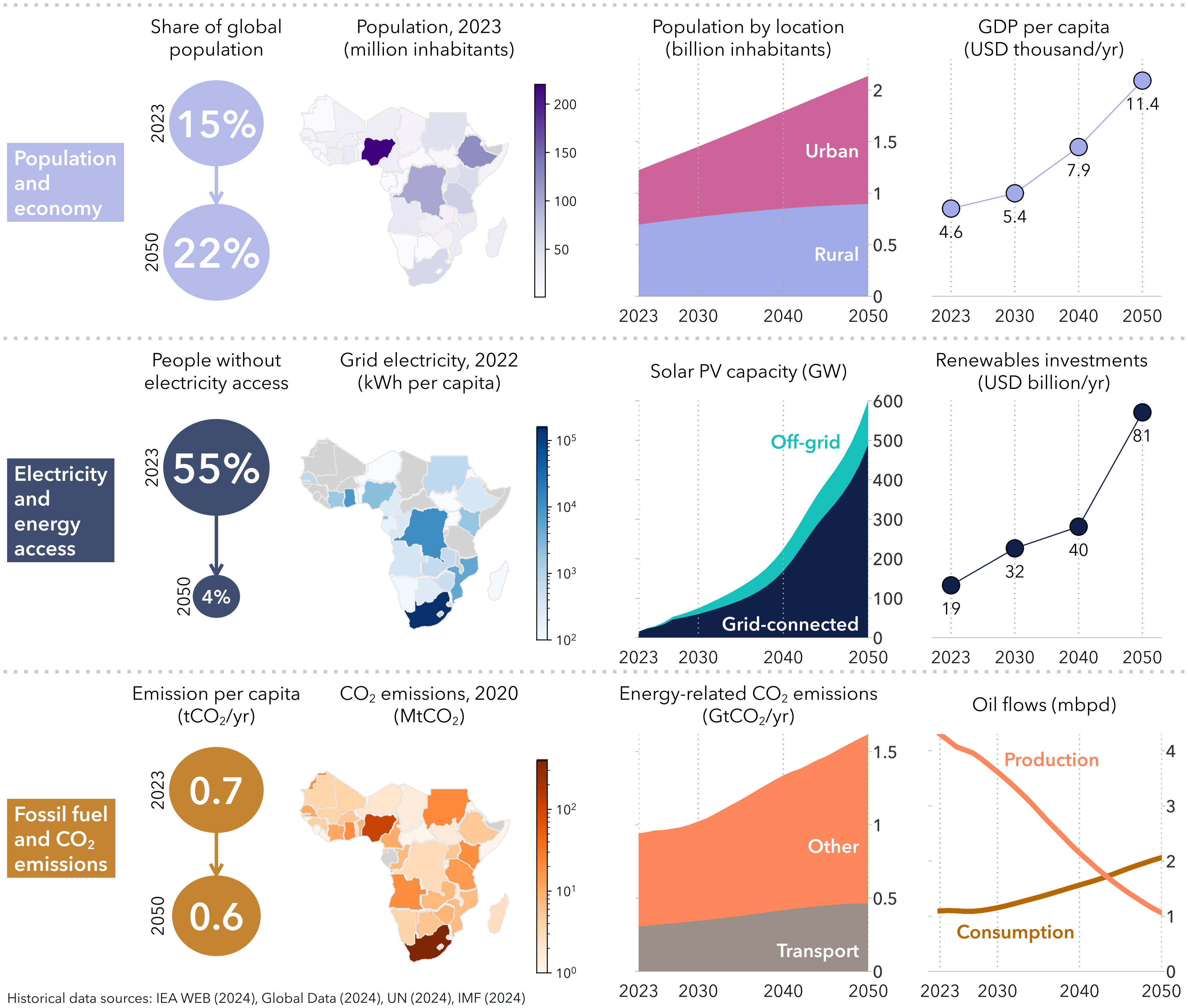
> The energy transition has a unique shape in Sub-Saharan Africa compared with the rest of the world: the region's projected economic development will be realized with a decrease in emissions per capita, a feature that no other region has achieved so far.

Figure 8.4.1 provides a series of indicators showing the subcontinent's unique current position and their forecasted development. Some key features include:

- **Rapid urbanization,** with urban population more than doubling from 2023 to 2050. Energy demand in cities is usually higher, with more affluent households and a higher density favouring grid buildout.
- **Wealthier economies** are related to urbanization. Together with the Indian subcontinent, Sub-Saharan Africa will experience the largest relative increase in GDP per capita. However, huge differences exist between countries in this region; GDP per capita currently spreads from USD 900/yr in Burundi to USD 20,000/yr in South Africa.
- **Increasing energy access** with off-grid solutions provides an affordable and scalable solution for low electricity-demanding applications.
- **A fast uptake of solar PV,** both on- and off-grid. Total uptake by 2050 will nevertheless remain small compared to the rest of the world, barely reaching the capacity of 650 GW already installed in China as of 2023.

FIGURE 8.4.1

Sub-Saharan Africa landscape and energy transition indicators



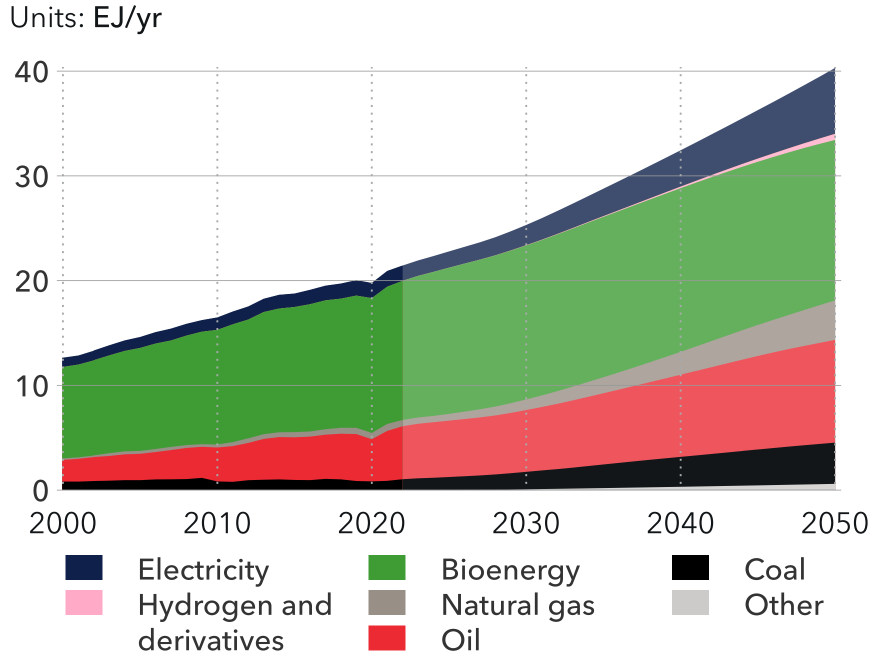
Historical data sources: IEA WEB (2024), Global Data (2024), UN (2024), IMF (2024)

A fuel mix dominated by bioenergy

No other region has a current or forecast fuel mix like the one shown in Figure 8.4.2. Its most striking feature may be the large share of bioenergy, specifically in buildings. The region represents of 30% of global bioenergy demand, taking first position globally. While this share may seem large, it reflects the region's small energy demand relative to its population. Europe and North America, for instance, have a slightly higher use per capita, but bioenergy represents less than 10% of the fuel mix. Biomass use is also not comparable to high-income regions.

FIGURE 8.4.2

Sub-Saharan Africa final energy demand by carrier

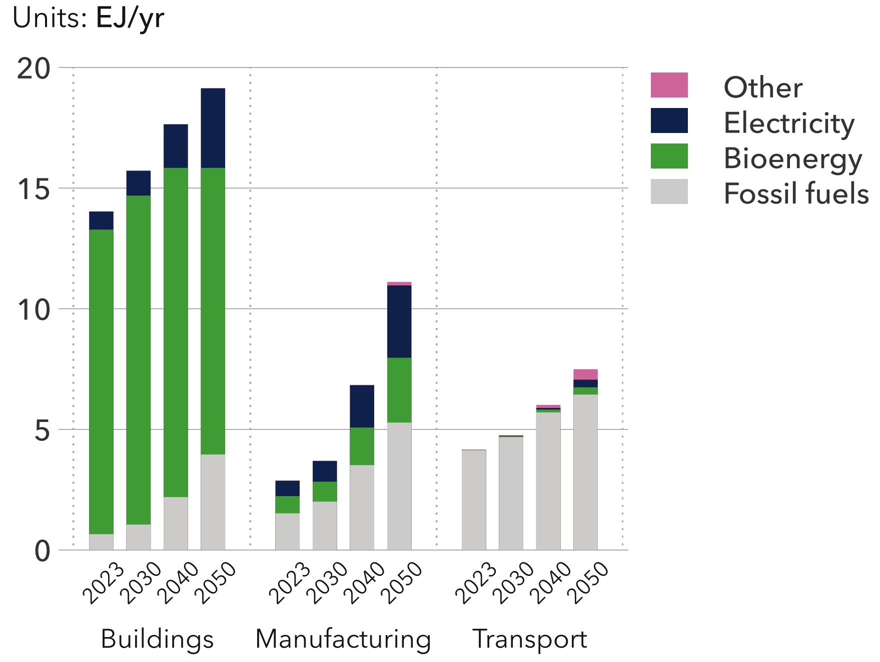


Historical data source: IEA WEB (2024)

Bioenergy is mostly used in the buildings sector, for cooking and water, and as traditional biomass (wood and charcoal) which is often self-harvested (Figure 8.4.3). This is one of the challenges of the region: lack of access to 'clean' cooking fuels causes well over one million deaths per year. Household pollution disproportionately affects women and girls, who spend more time engaged in household labour, which in turn impedes their access to social, health, and education services. This issue is receiving international attention, with initiatives like the *Summit on Clean Cooking in Africa* held in 2024. Going forward, fossil-fuel cooking is set to nearly double each decade, but increasing population and demand will keep traditional biomass-based cooking from declining until the mid-2030s.

FIGURE 8.4.3

Sub-Saharan Africa energy demand in selected sectors



These three sectors represent >93% of energy demand over our forecast period

> Off-grid electricity will be crucial for energy access, but will be used to supply low-power equipment.

The electricity uptake in buildings reflects the increasing demand for electrical appliances, lighting, and air conditioning (AC). The latter requires stable grids and will only be available in affluent cities. This explains the relatively low uptake of AC, despite sometimes unbearable temperatures in the region. This phenomenon is likely to worsen with climate change. As detailed later in this section, off-grid electricity will be crucial for energy access but will be used to supply low-power equipment, hence its minor share in total buildings demand. At present, it is possible to run ACs off-grid, but it requires substantial investment in panels, batteries, (to operate the AC at night) and other hardware, including a specialized mini-split AC unit.

Sub-Saharan Africa represented only 2% of global energy demand in the manufacturing sector in 2023. This reflects the low level of activity in the region, with low levels of industrialization, dominated by extractive industries and the export of raw materials with little further value added. The region is the most commodity-dependent in the world (UNCTAD, 2023) and in 2019, Africa's manufacturing value added (MVA) per capita of about USD 207 was about 12% of the global average (IRENA, 2022). Manufacturing will grow strongly, and its energy demand will increase on average by 5% per year to 2050.

The transport sector is presently 99% reliant on oil. As population and GDP per capita increase, so will the demand for transport for persons and goods. The number of passenger cars will increase almost three-fold over the forecast period, but car ownership will remain low and barely grow, from 2 to 3 cars per 100 inhabitants. While there are some initiatives in electric mobility, there is a lack of supporting policies and the region's electricity deficit also hinders electrification of road transport.

In that regard, future developments in Ethiopia should be closely monitored, as the country banned the import of gas-powered cars in February 2024, effectively becoming the first country in the world to ban ICEVs. This measure, primarily taken to avoid the trade deficit due to fuel purchase, is driving the uptake of (mostly Chinese) EVs. Almost 100,000 vehicles are already on the road (MOTL, 2024), in a country where about half of the population does not have access to electricity (IEA, 2019).

There is also uncertainty about the role of second-hand EVs coming from higher-income regions in electric uptake. Unlike petrol cars, used EVs might not be imported in Sub-Saharan Africa, as regions will avoid exporting valuable battery components that can be recycled.

Emissions

Our projection for the regional average carbon price level are USD 2/tCO_2 in 2030 and USD 20/tCO_2 by 2050 (Section 6.3). We expect slow adoption and limited explicit carbon pricing instruments in the region due to the predominant development focus. Future schemes will be motivated by access to climate finance and to avoid carbon-border adjustment mechanisms.

In the context of global climate policy, Sub-Saharan African country NDC pledges suggest the regional target is for emissions to grow no more than 68% by 2030 relative to 1990. These are unconditional targets, and some countries expect further reductions, provided there is international support.

Our Outlook indicates energy-related CO_2 emissions will almost triple over that period, suggesting that these ambitions will not be met. Looking ahead to 2050, very few Sub-Saharan African countries have adopted targets to reduce CO_2 emissions. Our Outlook estimates energy-related emissions of 1.4 $GtCO_2$ per year by mid-century, a further 57% increase from 2023 levels.

Electrification and energy access

Sub-Saharan Africa will leverage affordable and scalable renewable electricity, both on- and off-grid, to meet increasing demands and close the electricity access gap without going through the high-carbon phase that all industrialized regions have experienced.

Grid electricity, the backbone of transition

Sub-Saharan Africa's grid-connected electricity demand per capita is currently only one third that of the Indian Subcontinent and well below global average. It is even lower if one excludes South Africa, which accounts for one third of generation capacity from all sources.

A dramatic shift is predicted for the region's power systems, as is demonstrated by the changing on-grid electricity mix summarized in Figure 8.4.3. The renewable uptake will be backed by ambitious targets, such as Kenya aiming for 100 GW capacity by 2040. Renewable energy auctions have been implemented in Uganda, South Africa, and Zambia, while Ghana, Tanzania, and Kenya are adopting similar practice to boost the installation of new capacity.

At the same time, centralized fossil-fired power plants will not develop further; South Africa will be decommissioning coal-fired plants and both coal and oil-fired generation are set to decline across the entire region. In the short term, gas-fired generation will increase slightly, as countries like South Africa adopt this solution for their transition away from coal.

In other words, the region can and will leapfrog straight onto a pathway of low-carbon energy technologies. However, what matters to the subcontinent's development trajectory is not so much the percentage uptake of renewable in the power mix as the scale of electricity generation and availability. Unfortunately, while electricity generation will grow 5% year-on-year and quadruple from 2023 to 2050, Sub-Saharan Africa will still be the region with the least electricity generation.

One limiting factor is the insufficient interconnection between different countries in the region. This hinders the development of new utility-scale power plants and tapping into the vast potential of renewables like wind and solar PV. These sources are more vulnerable to poorly developed grids than fossil-fired power plants, as their integration requires a finely balanced and interconnected grid.

There is a combination of reasons for Sub-Saharan Africa's low grid development, among them lack of finance, technological know-how, and suitable business models. Projects in Sub-Saharan Africa will not face the same permitting issues experienced by higher-income regions with established power systems. This has been clearly acknowledged, and international support is building. One of the latest examples is the agreement between IRENA and AUDA-NEPAD to support a more 'interconnected, flexible, and reliable power grid' (IRENA, 2023). Regional initiatives like the African Single Electricity Market initiated by the African Union in 2021 are also important to build the essential cooperation for renewable power expansion.

The region will retain the lowest grid length per capita by far globally, with 330km per 100,000 inhabitants by 2050. The two other lowest GDP per capita regions, Indian Subcontinent and Latin America, will reach 1500km and 2200km, respectively, in that same period.

Off-grid will outpace slow grid developments

Despite all these developments, we still forecast grid access to stay low, with less than 20% of the population connected by 2050 (DNV, 2022). For users with very limited use of electricity – such as LED lightning, small refrigerators, and charging small appliances – grid charges represent an outsized fraction of electricity usage cost, which is why many

The challenge of modelling Sub-Saharan Africa

Energy forecasting requires access to quality data, and Sub-Saharan Africa is a challenging region in that regard. Institutional limitations, an important informal sector, and the outsized share of traditional biomass are key factors that led to a lack of quality energy demand and supply statistics. This contributes to greater uncertainty in energy modelling and analysis when it comes to policy design, market evaluation, and investment decisions compared to other regions. Several institutions like the IEA, the historical energy data provider for the ETO, are working to improve that situation (IEA, 2024). Thus, although DNV is confident about the trends detailed in this chapter, the absolute numbers should be viewed with caution.

urban areas in poorer parts of the world remain unconnected.

Photovoltaic electricity production can, however, be made cost effective via very small power-production units. Costing only a few dollars each, such systems allow for mobile phone recharging. Slightly more expensive systems (up to 500 W) can power household refrigerators and freezers when combined with batteries. Our analysis sees such off-grid installations outcompeting traditional small fossil-fuelled off-grid power generators.

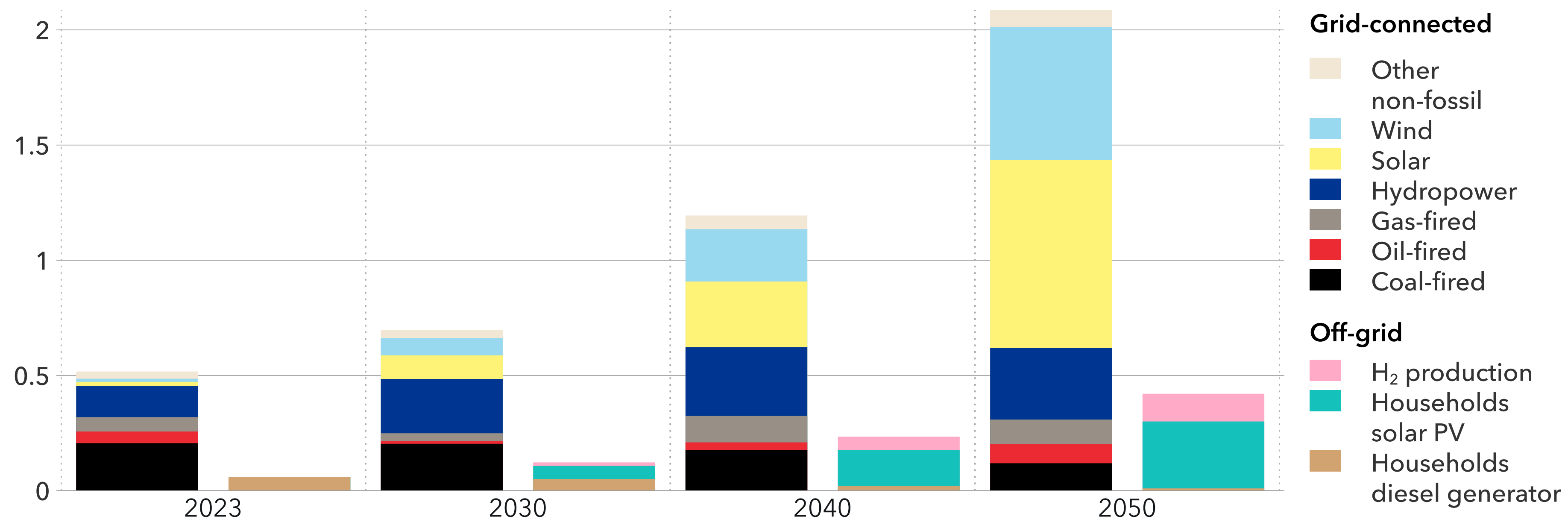
Microgrids also benefit from the modularity of small-scale PV and batteries. Typically connecting a few hundred electricity users and producers, such solutions afford the advantage of a grid (when some users have low demand, others have high) without the high grid costs. In principle, microgrids can be self-contained, that is, not connected to other microgrids or to larger grids with central power stations. In practice, our previous analysis shows that microgrids will typically be connected to higher-level grids. We see (DNV, 2019) such grid-connected microgrids representing 8% of solar PV production in Sub-Saharan Africa by 2050.

In energy terms, off-grid solutions can be classified as marginal. They are considered essential complementary tools to close the energy access gap as quickly as possible (World Bank, 2023).

FIGURE 8.4.4

Sub-Saharan Africa on- and off-grid electricity generation

Units: PWh/yr



Investments in the region

Although it currently represents only 3% of global energy investments, Sub-Saharan Africa is attracting attention from regional and international investors. The need is huge with the goal to help the region lift out of energy poverty and drive economic growth, without triggering an excessive rise in fossil fuels.

Insufficient development aid

In Sub-Saharan Africa, commercial and public finance dominate energy funding. Contrary to popular belief, less than 20% of energy investments come from foreign aid and concessional finance. The main challenge for boosting new energy projects, however, is accessing capital from both development finance and commercial sources.

With sufficient international aid, which also targets better governance, there is considerable potential for the continent to embrace the potential of a cost-effective, needs-oriented renewable energy strategy (IRENA, 2021). The call for global action was repeated at the Africa Climate Summit held in September 2023, but support is yet to materialize.

Challenges ahead

Sub-Saharan Africa is a challenging region for international investors who tend to be averse to uncertainty. Political instability in some countries in the region discourages substantial, long-term investments.

Corruption is also a pervasive problem across the subcontinent, exacerbating inequality, hindering much-needed development, and eroding access to vital services. Under these conditions, the traditional energy model of centrally controlled fossil-based power generation has faced challenges throughout the region.

Although it is historically responsible for a fractional number of global emissions, this region is likely to experience the most severe effects of climate change. Inadequate infrastructure is more likely to fail in extreme weather events, threatening fragile and complex energy systems. This additional risk also makes financing projects more expensive and less attractive.

Oil and gas are no new Eldorado

Close to half of Sub-Saharan Africa's export value is composed of fossil fuels, even though the subcontinent has a relatively small role in global fossil-fuel production, with respective shares of 4% for coal, 5% for crude oil and 2% for natural gas. There is a longstanding presence of international oil and gas companies Sub-Saharan Africa, and countries in this region rely on these players for the development of hydrocarbon resources.

Even so, we do not forecast an oil and gas boom in the region. On average, oil and gas assets in Africa are 15% to 20% more expensive and exhibit 70% to 80% higher carbon intensity compared with their global counterparts (McKinsey, 2022). As global oil demand declines, we forecast the region to become less attractive for investors. Recent examples include an abandoned gas project by Total Energies in South Africa (Reuters, 2024).

Additionally, many Western banks and financial institutions have adopted policies to cut back on backing fossil-fuel projects, particularly in Africa. This has resulted in a significant investment bottleneck in the continent's oil and gas sector, threatening megaprojects like the East African Crude Oil Pipeline (Economist, 2023).

As a result, crude oil production will continue to decline to around a quarter of today's level by 2050. The region will even become a net importer of oil products in the mid-2040s. On the other hand, natural gas production will almost double to 2050 after a plateau in the 2020s, following the increase in regional demand.

Declining petroleum export revenues will be a challenge. The region's oil producing countries are already struggling to transition into diversified economies; in both Angola and Nigeria – the region's largest economy – earnings from petroleum production make up 50% of government revenue. At the same time, there is a high dependence on imported refined products (USD 66bn in 2021), which more than offsets revenues from petroleum exports (USD 44bn) (World Bank, 2022). Nigerian businessman Aliko Dangote's new USD 20bn refinery recently (August, 2024) began operations, but its viability remains in the balance owing to an ongoing feud between the new refinery and those with vested interests in the flows of both crude exports and refined imports (McCormick and Adeoye, 2024).

Sub-Saharan Africa has clearly lagged in terms of renewable uptake, accounting for less than 2% of global investments from 2011 to 2020. However, as mentioned earlier, the future electricity mix will be dominated by renewable sources, with a wave of investments coming into the region (Figure 8.4.4).

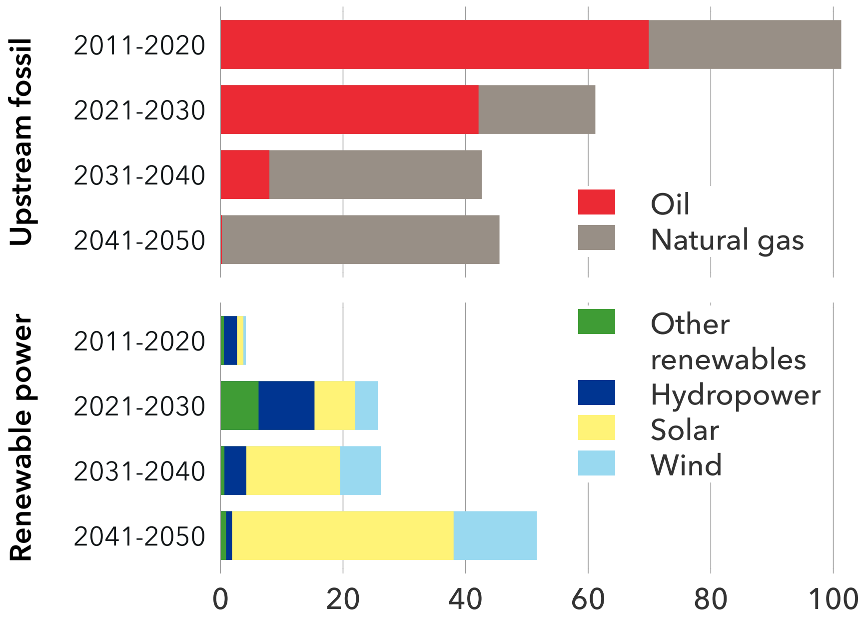
Large scale hydropower projects, like the Great Renaissance Dam in Ethiopia, show that the region still has great potential. Installed capacity will almost double in the next 10 years, leading to significant investments in the 2020s.

Investments in solar PV and wind will double every decade and overtake oil and gas investments in the 2040s. The region will represent 4% of global renewable power investments in the period from 2021 to 2050.

FIGURE 8.4.5

Sub-Saharan Africa average yearly energy investments

Units: USD billion/yr



International interest
The subcontinent's developing energy system finds itself at the crossroads of several global forces. As Sub-Saharan Africa explores relations with different international partners, it will be in a favourable position to obtain foreign investment.

China has been investing heavily in Africa, in particular through the BRI. Energy infrastructure is part of this program, and several power lines have been financed alongside numerous renewable power plants. However, with a looming economic slowdown, China's capacity to invest in Africa appears constrained in the medium term, and financing is becoming more targeted. The latest example is the pledge of USD 50bn in financial support to 2027, made at the China-Africa summit in September 2024.

China has expanded economic relations to become the region's largest trade partner, accounting for 20% of total trade value (IMF, 2019). Good economic relations mean that, with no trade tariffs in sight, competitive Chinese clean technologies will roll into the region. Renewable electricity uptake will be supported by affordable solar panels but also battery storage from the likes of BYD, allowing the integration of variables sources into weaker grids. The electrification of transport will be supported by Chinese products, especially for smaller mobility solutions.

As they compete with China, the US is paying heightened diplomatic attention to the region, as demonstrated by the December 2022 United States-Africa Leaders summit in Washington, DC (Jalata, 2023). US infrastructure investments may have been limited compared to China's, but that could be changing, as is evidenced by the recent financing of the Lobito Corridor, a railway stretching 1,300 km from DR Congo to Angola, which will facilitate the export of critical minerals.

Europe is still the second largest trade partner of Sub-Saharan Africa, after China. The EU launched a 'Global Gateway' in 2021, with an envelope of 150bn EUR for Africa, and the green transition is a pillar for investment for the continent. However, the winds of change are blowing. Energy investments in the region are intended to provide energy supply to Europeans, especially in oil and gas. Some European nations have felt pushback on this, facing criticism for what is perceived as a neo-colonial approach. A recent example is Niger's junta eviction of French multinational Orano from one of its largest uranium deposits in 2024.

Russia is trying to take advantage of the situation and accelerate the decline of European influence in Africa. Building nuclear power plants is a major export industry for the country. Burkina Faso and Mali, both military regimes backed by Russia, have recently signed declarations of intent with Rosatom to construct new power plants.

Some countries have positioned themselves as 'middle powers' on the subcontinent. The Gulf Cooperation Council states, and particularly the United Arab Emirates (UAE), are channelling billions into ports, mining, and clean energy sectors. Over the past ten years, Masdar, the UAE renewable energy investor, has developed energy infrastructure including five wind farms in South Africa, a battery energy storage system in Senegal, and solar power plants in Mauritania. Masdar has plans to invest USD 10bn to boost Sub-Saharan Africa's electricity generation capacity by 10 GW. It is not just renewables that attract investments from the UAE; in May 2024, the Abu Dhabi National Oil Company acquired a 10 percent stake in Mozambique's Rovuma gas basin from Portuguese energy company Galp for approximately USD 650m.

Turkey is also trying to expand its presence in Sub-Saharan Africa. Energy is not a main priority, but the country signed an agreement on oil and gas exploration and production with Somalia in July 2024.

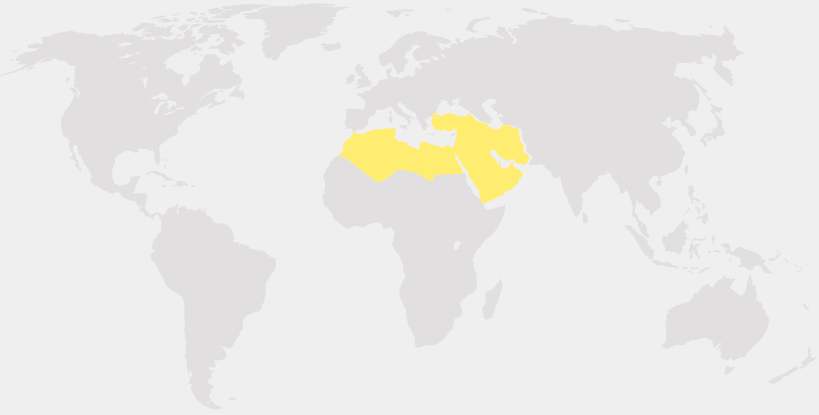
Supporting global decarbonization efforts
There is rising interest in the subcontinent's rich endowment of natural resources. Primary goods (agricultural products, minerals, metals, and fossil fuels) currently dominate the region's exports. Critical minerals for the energy transition will continue to attract interest to the region. DR Congo, for example, represents more than two thirds of global production of cobalt currently used in batteries. Countries in the region are keen to extract more value from secondary and tertiary refined products as well, but there are many challenges to overcome (ZCA, 2024).

Availability of hydropower and access to some of the best solar and wind resources in the world mean that the production and export of green hydrogen and ammonia will be competitive in some areas in the region. Namibia is willing to pioneer this industry, with its ambitious USD 20bn Green Hydrogen Programme.

There is also significant potential to contribute to decarbonization through the maintenance and further expansion of forests as natural carbon sinks. International companies seeking to lower their footprint are willing to buy high-quality carbon credits from the regions, potentially generating billions of dollars in revenues for the region (UNECA, 2024).

8.5 MIDDLE EAST AND NORTH AFRICA (MEA)

This region stretches from Morocco to Iran, including Turkey and the Arabian Peninsula.



Algeria, Egypt, Iran, Israel, the Kingdom of Saudi Arabia, Turkey, and the United Arab Emirates account for **80%** of region energy use.

	Population (Million)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/person (tonnes)
2023	575	13.4 23 000	57 99	3.1 5.4
2050	770	28.3 36 600	75 103	2.8 3.6

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.5 MIDDLE EAST AND NORTH AFRICA (MEA)

Current position

The region is home to 52% and 43% of global oil and natural gas reserves, respectively, but the energy landscape is diverse in terms of energy conditions.

Major fossil-fuel exporters cooperate in the Gulf Cooperation Council (GCC) to further power resilience through interconnection. State-owned companies and sovereign wealth funds are transition-investment vehicles with concerted efforts to engage in the global trend towards renewable energy and low-carbon technologies and to diversify economies, but they also continue to invest in hydrocarbons. In 2024, energy investments in the Middle East region are projected to reach approximately USD 175bn, with 85% allocated to oil and gas (IEA, 2024).

Other region countries are non-fossil fuel rich with energy trade deficits: Turkey, Morocco, Jordan, and Lebanon depend on imports (natural gas and oil) for their energy needs and seek ways to diversify their energy portfolios. Turkey, for example, is pursuing solar, wind, and storage uptake, nuclear generation, and development of natural gas fields (Siccardi, 2024).

The energy supply mix is fossil-fuel dominated, 96% in 2023. On the back of growth in populations and electricity consumption, energy-related emissions are rising.

Several region countries have pledged to decarbonize their economies by or around the middle of the century: the United Arab Emirates (UAE), Israel, and Oman with net-zero targets for 2050; Turkey for 2053; and Bahrain, Kuwait, and the Kingdom of Saudi Arabia for 2060. However, unfolding conflict disrupts energy transition focus and hence net-zero aspirations.

Climate change adds stresses to the region, such as soaring heat, extended droughts, threatening food and water security. Unusual precipitation and floods in Oman and the UAE (April 2024) had losses estimated at more than USD 8bn (Munich RE, 2024).

Pointers to the future

- The region is at a critical junction with great potential for accelerating the energy transition nationally and globally. Significant jobs and GDP benefits are possible from linking climate, development, just transition (up-and reskilling), and industrial policies (ILO et al., 2023).
- With abundant fossil and renewable resources, the region is well placed for the COP28 promised transitioning away from fossil fuels. The region will hold the cheapest hydrocarbon production costs and can balance supply to the market, but with a greening twist, as seen in the Oil and Gas Decarbonization Charter (COP28) that aims to accelerate decarbonization of operations, reduce emission intensity and promises investments in negative emissions technologies.
- COP27 and COP28 hosted by the region have some catalytic effect on decarbonization actions. However, policies are predominantly focused on the supply side: renewable electricity encouraged by national targets and mainly supported through tenders and auctions for 20 to 25-year PPA contracts with state entities, or as in Turkey through 10 to 15-year feed-in-tariffs, and also increasingly coupled with renewable hydrogen ambitions. CCS developments among hydrocarbon exporters leveraging state-owned / national oil companies’ financing (Fattouh et al., 2024), in part motivated by the emerging low-carbon hydrogen export market. E-mobility is pioneered in select countries, but broad adoption hindered by fossil-energy subsidies and lack of carbon pricing.
- The extent of decarbonization beyond the power sector is uncertain given less pronounced domestic policies. However, sitting at the gateway of Europe, the region as an energy hub will have to transform from gas exports in the short and medium term to green energy in the longer term.

Energy transition: oil and gas for export and modest diversification at home

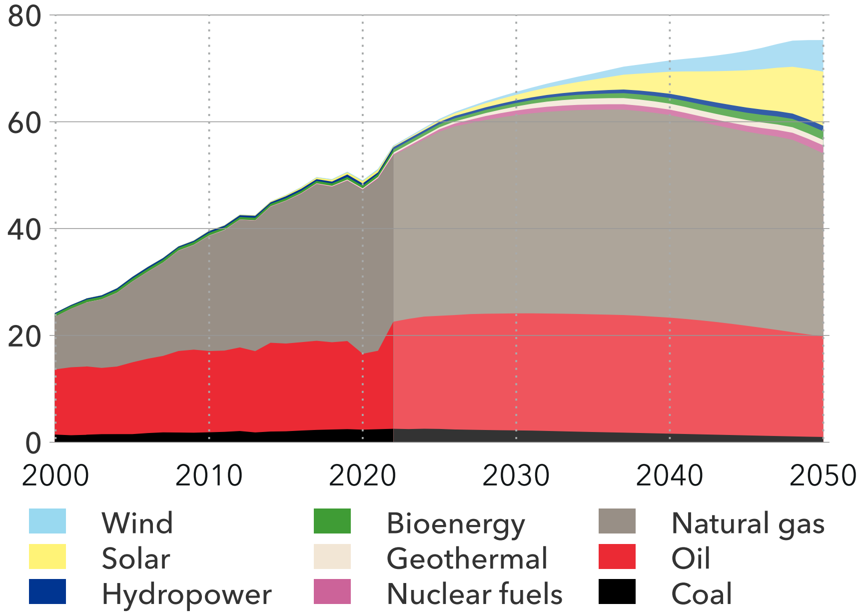
The Middle East and North Africa is a diverse region, from extremely wealthy countries like Qatar to less developed countries like Syria. Most of the countries are oil and gas exporters, with Turkey as the largest exception, and oil and gas production dominates the region's economy.

Despite recent growth in green initiatives, the region remains fossil-fuel dependent. Figure 8.5.1 shows developments in primary energy supply for the Middle East and North Africa region. Primary energy is expected to grow by 33% over the next three decades, from 57 EJ in 2023 to 75 EJ in 2050. Most of this growth is in the next decade as the annual gas supply rises from nearly 32 EJ to 38 EJ. Energy supply grows by only about 10% between 2032 and 2050 due to greater electrification of various sectors and a doubling in non-fossil energy carriers with higher efficiency.

FIGURE 8.5.1

Middle East and North Africa primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2024)

By 2050, with 26% renewables in the primary energy supply mix, this oil and gas-rich region will still rely predominantly on fossil fuels, even though today's shares of oil, gas, and coal are all expected to fall. Despite hardly any coal use, the region's fossil fuel share will be at 71% in 2050, the second highest of all regions after North East Eurasia. Of renewable energies, solar (14%) and wind (8%) show the most growth, but regardless of its sunny conditions, the region has the second lowest share of solar of all regions.

It is therefore fair to say that the regional transition is relatively slow when comparing the potential with the overall likely achievement, and the convenience of vast amounts of low-price oil and gas is a huge challenge for further acceleration.

Renewables slowly dominating electricity production

All over the region, green initiatives are adding to the fossil fuel picture. For example, this year the Egyptian government allocated about 6 million square metres of land for the development of 27 GW of solar and wind projects, contributing significantly to Egypt's goal of generating 42% of its electricity from renewable sources by 2030 and 60% by 2040 (Enerdata, 2024; Barakat, 2024; Egypt Today, 2024). Morocco already has half its electricity from renewables, generating 1.3 GW from hydropower, 1.6 GW from wind, and 0.85 GW from solar, all in 2023.

Figure 8.5.2 visualizes trends in on-grid electricity generation by power station type for the region. In this picture, the transition is much more marked than for overall primary energy. Between 2023 and 2050, annual electricity generation triples, from 2,100 TWh today to 5,900 TWh by 2050. Still, electricity will only represent 28% of all final energy in mid-century, double of the 15% it represents today, but still among the lowest in all the regions.

While almost absent from the current mix, we expect solar and wind will provide 49% and 31%, respectively, of the region's electricity by 2050. A third of this solar electricity generation will be in solar+storage. Most of the wind power will be onshore in our forecast, with fixed offshore wind farms constituting 17% of total generating capacity and floating offshore expected to be around 2% by mid-century. In the first decade, the green electricity comes on top of, not instead of, fossil electricity. However, after 2035, fossil electricity will be in sharp decline, with the share of gas, oil, and coal in power generation projected to decrease from the current levels. Notably, natural gas's share drops from 70% today to 8% in mid-century.

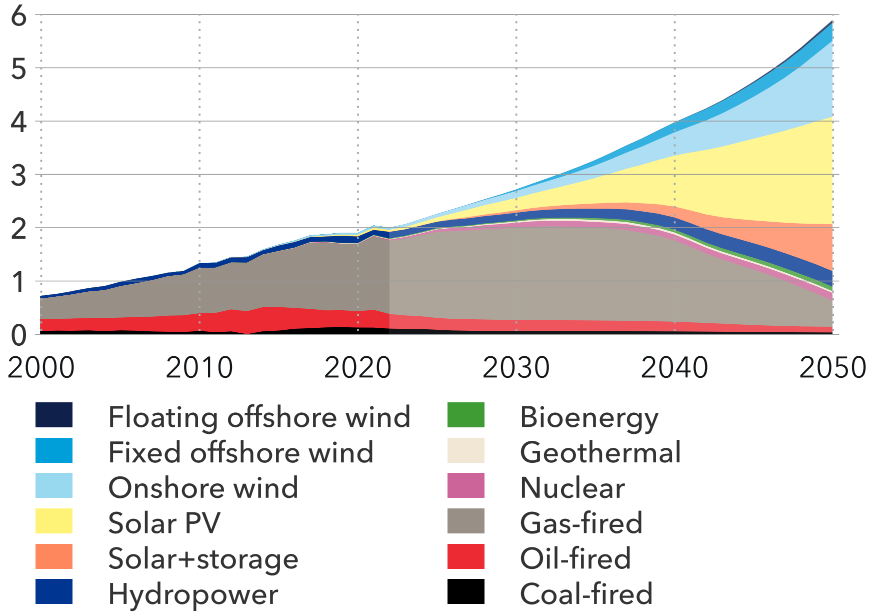
The GCC Interconnection Authority (GCCIA), was established in 2001 to link the power systems of the six GCC countries. As of 2024, the GCCIA has significantly enhanced its power capacity, managing 5100 MW (GCCIA, 2024). Additionally, they began a project to connect the GCC grid with Iraq. As of 2023, Iraq's Basra province is set to receive 500 MW from the GCCIA, with a potential expansion of up to 1.8 GW in the future (Al Maleki, 2023).

The current conflict between Israel and Hamas/Hezbollah has a significant escalation potential both politically and militarily and is therefore a potential threat to fossil-energy supplies from the region. The conflict could also influence global energy prices and add to the national and energy security focus and budgetary pressure, with longer term energy transition priorities suffering.

FIGURE 8.5.2

Middle East and North Africa grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2024), GlobalData (2024), IRENA (2024)

Final energy demand

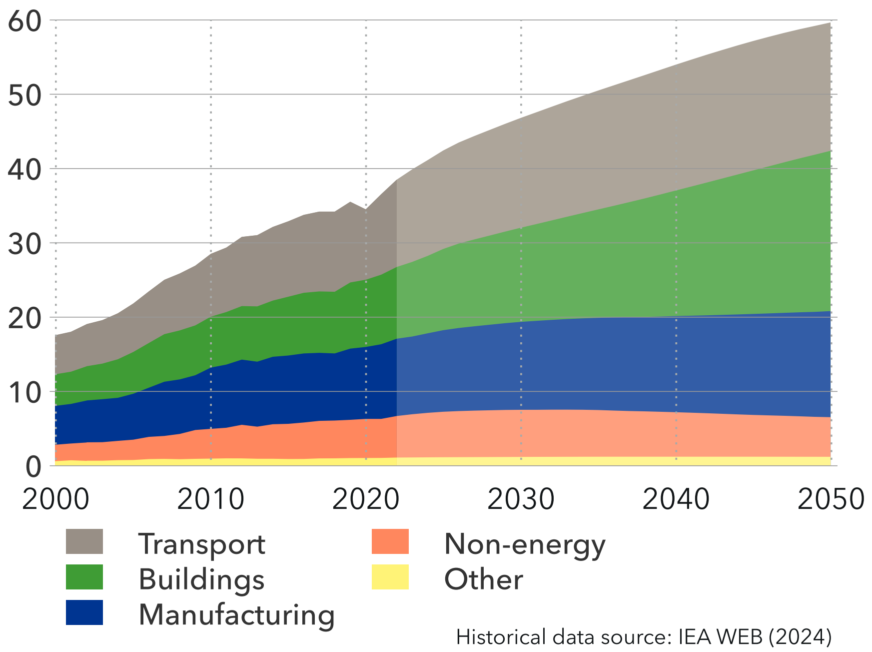
Figure 8.5.3 depicts the growth in total energy demand by the demand sector from 1990 to 2050. In line with a 34% growth in population and a more than doubling of the size of the regional economy, total energy demand rises 50% over the next three decades, from 40 EJ in 2023 to 60 EJ in 2050.

In 2023, energy demand in the transport sector was 13 EJ, making up 31% of the total energy demand. Of this, 82% was attributed to the road transport sector. Many of the fossil-fuel-producing countries in the region are heavily subsidizing fossil fuel, including gasoline for passenger vehicles, and this provides little incentive for reducing oil use in the road sector.

FIGURE 8.5.3

Middle East and North Africa final energy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2024)

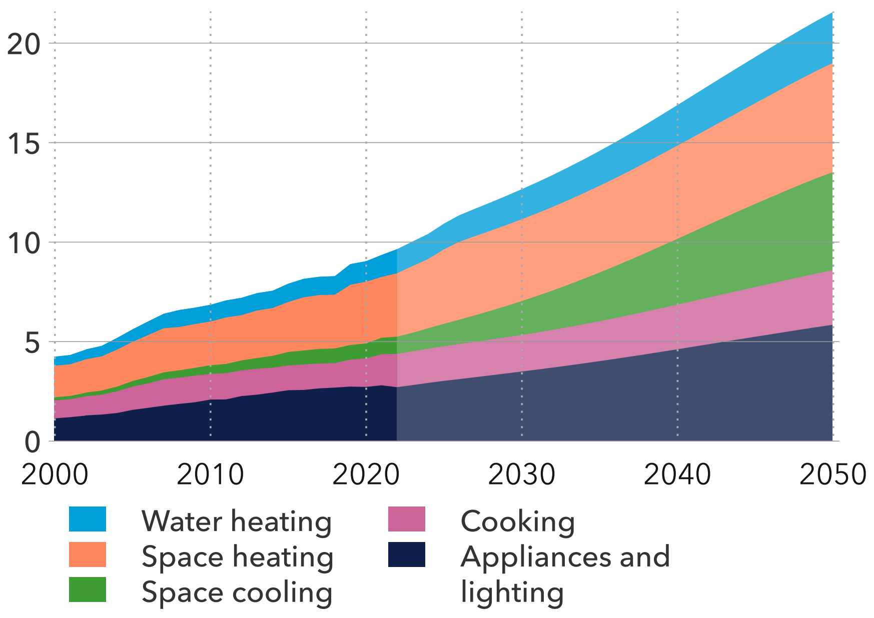
Despite the well-known effect of subsidies, there seems to be little willingness to stop this tradition, which forms part of the governmental 'contract' with citizens.

Annual demand from road transport is expected to peak around 14 EJ by 2045, then gradually decline due to the rise in EV adoption. Ambitions of EVs are relatively high, with the UAE aiming for 10% of new car sales to be EVs by 2030 and 50% of passenger vehicles by 2050. Saudi Arabia targets 1 to 2 million EVs by 2030, with 30% of vehicles in Riyadh being electric. Morocco is expanding its infrastructure for heavy electric trucks. Turkey aims for 1 million EVs by 2030, and Israel targets all new cars to be electric by 2035 (Voice of America, 2024; GulfNews, 2024; Samra-Rohte, 2024; Khamis, 2023). Still, DNV forecasts electricity to account for only 12% of the road transport energy mix by mid-century.

FIGURE 8.5.4

Middle East and North Africa buildings energy demand by subsector

Units: EJ/yr



Historical data source: IEA WEB (2024)

The fastest-growing demand sector is buildings, with space cooling its fastest growing subsector (Figure 8.5.4). Out of the total 11 EJ growth in annual total energy demand in all sectors, 37% originates from a surge in demand for space cooling, which grows more than fivefold. This despite a 25% improvement in the average efficiency of cooling equipment, which means useful energy demand for space cooling is expected to grow even more rapidly. This rise in demand for space cooling is due in part to the warming climate – leading to a 30% increase in the number of cooling degree days by 2050 – and even more to the growing standard of living. The economy sees a doubling of GDP per capita in the region, ensuring a more than doubling of building floor area.

Manufacturing also shows a significant growth in the forecast period, with a 36% increase in final energy demand to 2050. The region's ample amount of cheap gas is a competitive advantage for producing energy-intensive products such as fertilizer and alumina, and the price of carbon remains low through the entire period. With plentiful gas, hydrogen will also be cheaper than in many other regions; this hydrogen can be decarbonized, making competitive low-carbon products cheaper than most other regions.

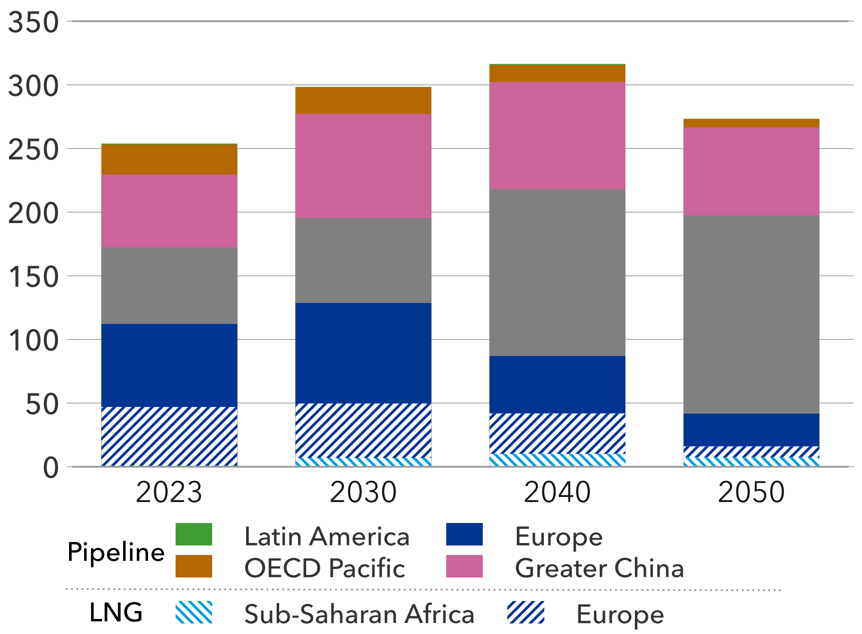
Big Oil in the Middle East gets bigger

The Middle East has the cheapest oil and gas, and as global demand peaks, this will decide which region remains the dominant producer (see Chapter 4) in this Outlook. By 2050, we project oil and gas production in the region will increase to 36 Mbpd and 1 300 bcm, respectively, accounting for 63% of the global oil share and 31% of the global gas share. The region's oil exports are primarily directed to China, Europe, India, Japan, and South Korea. However, the invasion of Ukraine altered market dynamics, increasing exports to Europe while decreasing exports to China and India due to competition from cheaper Russian oil. Figure 8.5.5 shows the region's gas export destination via LNG and pipeline. Although gas demand in Europe is projected to decrease, leading to reduced exports

FIGURE 8.5.5

Middle East and North Africa gas export via pipeline and LNG

Units: Bn m^3/yr



to this region, LNG demand in China and India is expected to rise over the next two decades.

Although the region is dominated by large oil and gas producers, there are notable exceptions: Turkey in particular, is a large importer. Several of the countries that do not have oil or gas are lagging in terms of economic development, but renewable energy provides an opportunity for these countries to increase their energy independence. Turkey is also a gateway to Europe and is strategically located between the oil rich countries in the GCC and the EU. In terms of fossil-fuel dependence, however, Turkey is likely to resemble its Middle Eastern rather than its European neighbours, which are decarbonizing much more quickly.

Hydrogen export potential

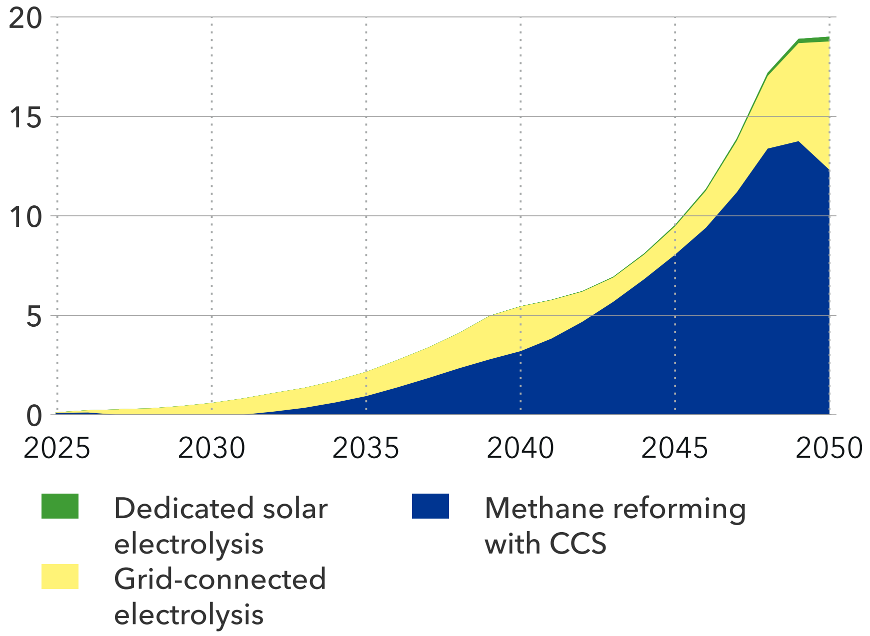
Hydrogen has a role to play in the region. In the Gulf, Saudi Arabia, UAE, and Oman have issued ambitious hydrogen strategies and are set to exploit abundant access to solar and wind power and use natural gas reserves for blue hydrogen. Saudi Arabia plans to produce green hydrogen using 4 GW of renewable energy at its NEOM project, which is expected to be operational by 2026. The UAE aims to capture 5 million tonnes of carbon annually by 2030 to support its hydrogen production and overall decarbonization goals (Oxford Business Group, 2022; Obeid, 2024). In 2024, Egypt secured partnerships with international developers, highlighting its strategy to become a central hub for green hydrogen and ammonia production (Daily News Egypt, 2024). Figure 8.5.6 shows the growth of annual hydrogen production (as an energy carrier) in the Middle East and North Africa starting in the 2030s. From virtually zero today, it will grow to around 1 Mt in 2030 and 23 Mt in 2050.

The rates of growth for blue hydrogen (from methane reforming of natural gas with CCS) are much higher than green hydrogen (via electrolysis using grid-connected electricity) for the forecast period. Thanks to low prices for locally extracted natural gas, blue hydrogen remains the most economically viable route throughout the forecast period. The Levelized Cost of Hydrogen (LCOH) for blue hydrogen, the second cheapest after grey hydrogen, is expected to decrease by 40%, from 2.4 to USD 1.5/kgH₂. However, with the rapid growth in solar electricity generation and associated cost reductions due to learning curves, we project LCOH for grid-connected electrolysis production will decrease by 50%. Consequently, grid-connected electrolysis will grow faster toward the end of the forecast period.

FIGURE 8.5.6

Middle East and North Africa hydrogen production as energy carrier

Units: MtH_2/yr

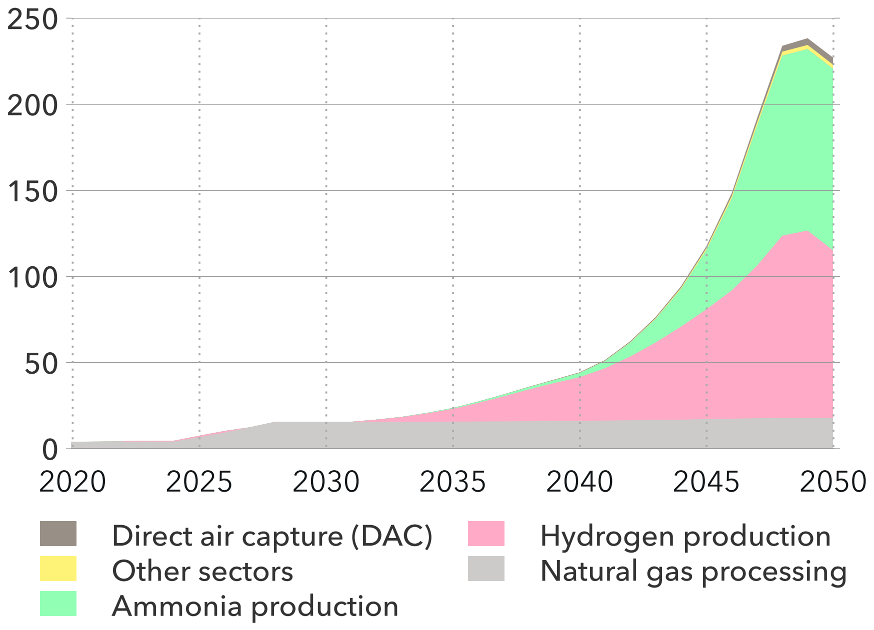


Regional demand for hydrogen will be moderate and lower than its production. Due to the cost-effective production of low-carbon hydrogen and derivatives, as well as the region's ideal location at the nexus of growth markets across the eastern and western hemispheres, Middle East and North Africa countries are set to become the largest global suppliers in the emerging global hydrogen market. Some 12 Mt/yr of hydrogen is expected to be exported via pipeline and seaborne trade in 2050 – mainly to Europe, Japan, and South Korea – as well as around 70 Mt/yr of ammonia via shipping. Although no other regions export more hydrogen and ammonia than the Middle East and North Africa, the numbers are still relatively small and dwarfed by oil and gas exports. Its 12 Mt of hydrogen correspond to less than 0.3% of the global final energy demand, and 70Mt of ammonia corresponds to about the same.

FIGURE 8.5.7

Middle East and North Africa CO_2 emissions captured by sector

Units: $MtCO_2/yr$



As hydrogen and ammonia production expands across the region, prominent entities like Aramco, ADNOC, and Qatar Energy have teamed up with global firms to explore and capitalize on opportunities within blue hydrogen and CCUS projects. Qatar, Saudi Arabia, the UAE, and Oman have CCUS projects in development, under construction and already operating, with a combined annual capture capacity of 19.5 $MtCO_2/yr$ (operational capacity is 4.3 $MtCO_2/yr$ as of December 2023). There is also a range of planned projects in the GCC countries; these forward-looking initiatives underscore the region's high ambitions on CCS.

We do not think all projects will go forward, and the CCS uptake in the coming decade will be modest. Figure 8.5.7 shows the forecast ramp-up of CCS and DAC in the region, with almost all the CCS in 2050 being in blue hydrogen and blue ammonia projects. Total emissions captured of about 230Mt in 2050 correspond to roughly 8% of all energy related emissions, and the potential for doing more CCS in other sectors such as industry and power remains significant.

The region also has potential for DAC, but the forecast level is only 3 Mt in 2050; we expect very low government push for this, in line with low costs of carbon.

Emissions peaking in the 2030s

Carbon pricing is presently low or negative given fossil-fuel subsidies, and we expect slow adoption. Our projection (see Section 6.2) for the regional average carbon-price level is USD 10/tCO_2 in 2030, USD 20/tCO_2 in 2040, and USD 30/tCO_2 in 2050.

In the context of global climate policy, country pledges in nationally determined contributions (NDCs) indicate that the Middle East and North Africa, viewed as a region, has a target for emissions to increase by no more than 231% by 2030 relative to 1990. Our Outlook suggests that energy-related emissions after CCS (CCS volumes are shown in Figure 8.5.7) will have increased by 264% by then, demonstrating that emission targets will not be met. There are, however, some uncertainties in the comparisons of targets and forecasts, as some country pledges are unclear about whether the targets reported in NDCs also include non-energy related CO_2 emissions. Most Middle Eastern emission targets are given relative to a business-as-usual trajectory.

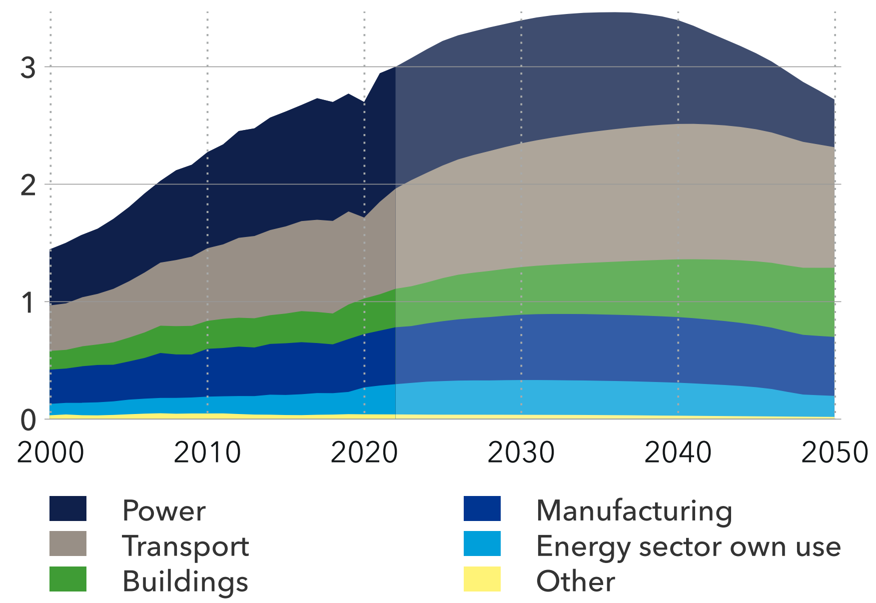
Energy-related CO_2 emissions are expected to keep rising until the mid-2030s, when they peak at around 3.5 GtCO_2/yr, approximately 14% above today's level. In 2050, energy-related CO_2 emissions (after CCS and DAC) in the region are expected to have decreased by around 11% compared with 2023 levels to 2.7 GtCO_2 annual emissions. Figure 8.5.8 shows that over the past three decades, the power sector has consistently contributed to one-third of total emissions. However, as renewables increasingly dominate power generation, the transport sector is set to become the largest emitter, projected to reach 38% of total emissions by 2050.

Today the region's per capita energy-related CO_2 emissions stand at 5.4 t per person, which is 125% of the global average. By mid-century, the per capita emissions will fall to 3.5 t per person in 2050, but this is slower than the global average and still double the global average emission of 1.8 t per person.

FIGURE 8.5.8

Middle East and North Africa energy-related CO_2 emissions by sector

Units: GtCO_2/yr



Historical data source: IEA (2024)

Manifa Field Causeway.

8.6 NORTH EAST EURASIA (NEE)

This region consists of Russia, Mongolia, North Korea, and all the former Soviet Union states, including Ukraine but not the Baltics.

Russia, Ukraine, and Kazakhstan account for **80%** of region energy use.

	Population (Million)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/person (tonnes)
2023	320	7.1 22 100	44.7 139.5	2.3 7.3
2050	334	10.4 31 100	40.6 121.7	1.9 5.7

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.6 NORTH EAST EURASIA (NEE)

Current position

The region has plentiful oil, gas, and coal reserves making the region a net exporter. Russia is the world's third and second largest producer of crude oil and natural gas, respectively, and the largest in enriched uranium exports. Kazakhstan is rich in oil, gas, and coal and is a leader in uranium mining (42% of world production) with dependence on exports in GDP and government revenue.

Control over the energy sector is part of the consolidation of power with the regime in Russia and hydrocarbon exports are instrumental for Russia to finance war efforts and domestic social obligations. As the European market declined, China, India, and Turkey are now the top three buyers of Russian fossil fuels (Raghunandan, 2024).

Between 2022 and 2024, Russia regularly struck Ukrainian energy infrastructure with missiles and drones. An estimated half of Ukraine's power generation capacity has been lost – either occupied, destroyed, or damaged.

Population levels and energy demand have stabilized in the region and emissions have peaked. Economies are among the most energy-intensive globally, relying on fossil fuels for close to 90% of energy supply. However, countries like Kazakhstan and Uzbekistan are taking steps to diversify economies, turning to solar and wind power and driving a shift to renewable energy in the region.

Russia is increasingly isolated from the international community's efforts to reduce GHG emissions, although Kazakhstan, Russia, and Ukraine announced targets for carbon neutrality by 2060.

Climate risks include heat waves, drought, and wildfires, and thawing of Russia's permafrost with associated soil instability and infrastructure damage.

Pointers to the future

- Transition and decarbonization efforts gain momentum, balanced by a continued willingness to exploit fossil-fuel resources.
- There is growing evidence of activity and interest from international investors to leverage renewables potential in power.
- Kazakhstan targets 15% of its electricity from renewables by 2030 and 50% by 2050. Between 2023 and 2024, Kazakhstan signed deals with Saudi Arabia's ACWA Power, the UAE's Masdar, and France's TotalEnergies for construction of 3 GW of wind power capacity with integrated storage systems (Zabanova, 2024). The memorandum of understanding with the EU related to batteries, raw materials, and renewable hydrogen enters a roadmap development stage for concrete joint actions.
- Uzbekistan aims for 25% of energy needs from renewables by 2030 and increased solar and wind capacity by 5 GW and 3 GW, respectively. It signed an agreement (2023) with UAE's Masdar to develop over 2 GW solar and wind and 500 MWh of battery energy storage.
- Other countries expand relations with the EU, such as the planned *Green Energy Corridor* between Azerbaijan, Georgia, Romania, and Hungary to construct the *Black Sea Energy* submarine electric cable connecting Azerbaijan's future offshore wind farm with Europe.
- Ukraine's *National Energy and Climate Plan* (June 2024), developed as part of the integration process for future EU membership, serves as a blueprint for energy reconstruction and green renewal and to attract international assistance. Key *NECP* elements are: 27% share of renewable energy sources in energy consumption by 2030 and diversification of energy sources and supply routes. Investment needs total USD 41.5bn (Energy Community, 2024).


Solar panels in Ukraine

Energy transition: holding on to fossil fuels but making a start with renewables

Our previous Outlooks have highlighted that countries heavily reliant on exporting fossil fuel are likely to be slow in transitioning to renewable energy. This is particularly true for nations in North East Eurasia, where governments are often autocratic and there is limited influence by the public over policy decisions. These regimes typically show little interest in investing in the substantial changes required for a successful energy transition. The lack of political will and the entrenched interests in fossil fuel industries make these countries more resistant to adopting cleaner energy alternatives, leaving them lagging in the global shift towards renewables. The continuing war in Ukraine, started by Russia in 2022, further complicates the energy transition path for the region. Being effectively isolated from the western front-runners of the energy transition, Russia continues to emphasize its fossil-fuel production and exports, redirecting them to the East, mostly to China. For Ukraine on the other hand, as we describe further in the section, rebuilding damaged energy infrastructure opens opportunities for scaling up its renewable energy, in particular solar. These positive developments might potentially spur other former Soviet Union countries in the region to enhance their energy systems with clean and more secure supplies.

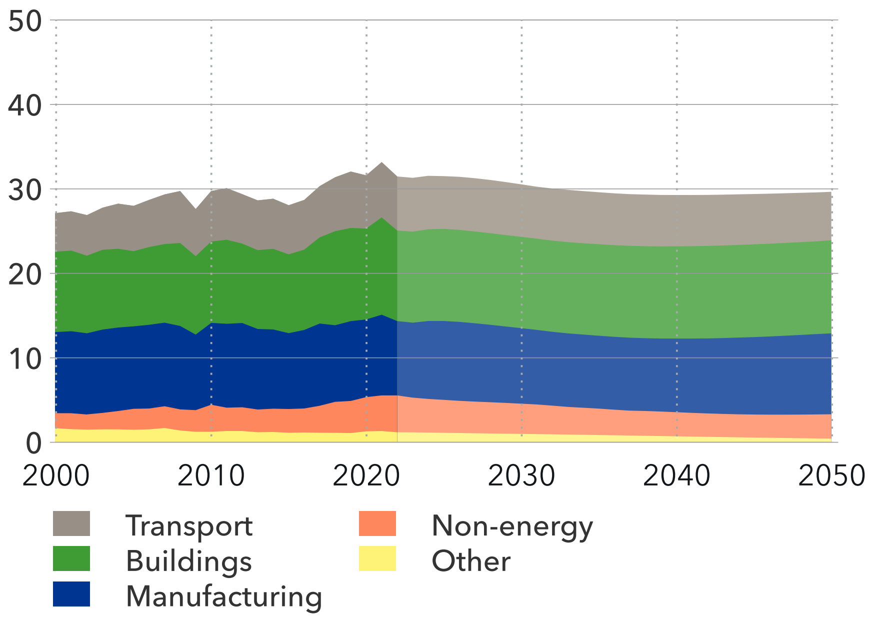
The laggard nature of the region in the context of the energy transition is well illustrated by our forecast, which shows that its energy system generally retains today's characteristics through to mid-century. Final energy demand in 2050 is only about 5% lower relative to current levels, with a similar sectoral split and little change in the mix of energy carriers (Figure 8.6.1 and Figure 8.6.2). Fossil energy remains at current levels, though electricity creeps up at the expense of coal, as buildings owners and users take advantage of electricity's added convenience.

We foresee similar developments in primary energy demand (Figure 8.6.3). Natural gas continues to dominate, constituting slightly more than half the

FIGURE 8.6.1

North East Eurasia final energy demand by sector

Units: EJ/yr

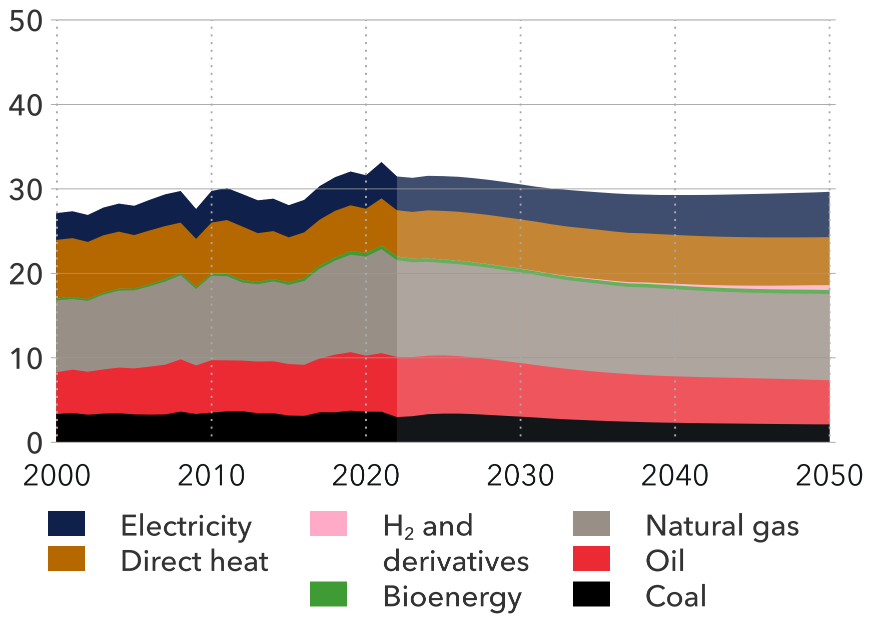


Historical data source: IEA WEB (2024)

FIGURE 8.6.2

North East Eurasia final energy demand by carrier

Units: EJ/yr

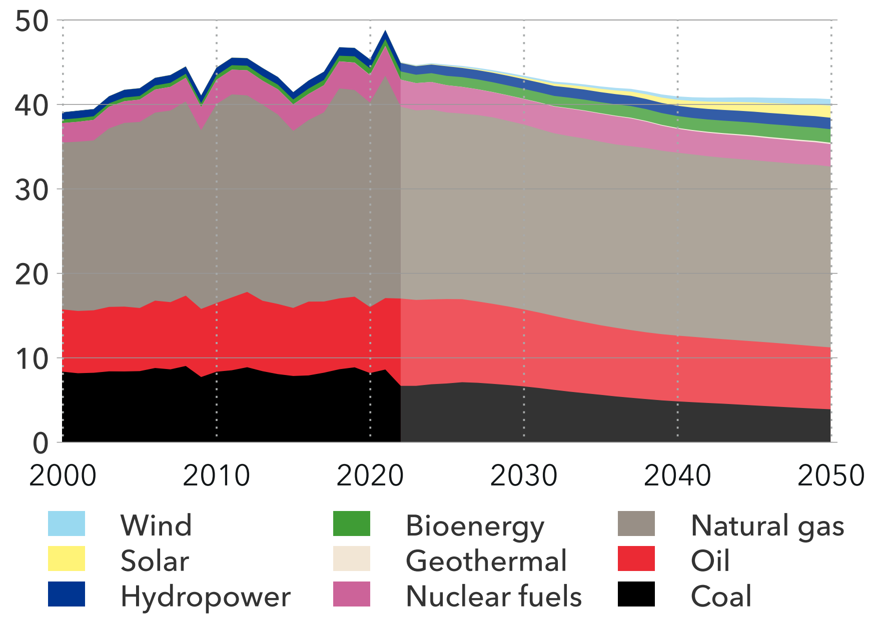


Historical data source: IEA WEB (2024)

FIGURE 8.6.3

North East Eurasia primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2024)

mix. On the non-combustion side, solar and wind will grow strongly relative to their currently negligible shares reflecting ambitious targets (relative to the rest of the region) for renewables in Kazakhstan and Ukraine. However, despite the growth, solar and wind will provide only about 4% and 2% of primary energy, respectively, in 2050.

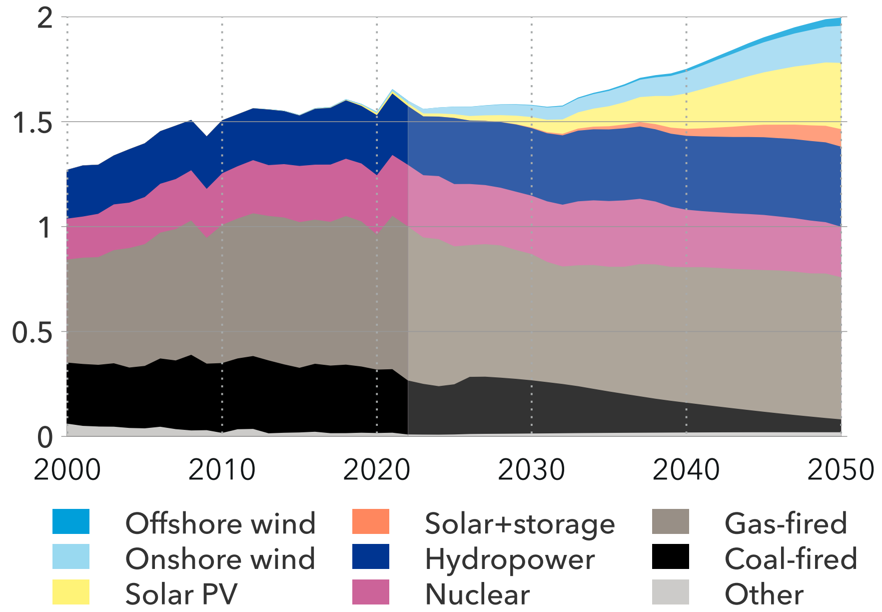
Renewable power: an emerging opportunity for solar

The 28% increase in electricity production to 2050 will mostly come from renewables, but gas will still provide close to one third of power in 2050 (Figure 8.6.4). Low domestic gas prices – also benefitting from lost export opportunities because of the Ukraine war and continued sanctions even after the war eventually ends – make coal less competitive, and its share in power production reduces from 16% presently to 3% in 2050. By mid-century, hydropower output will have increased by 36% to generate almost a fifth of the region's electricity. Growing from virtually nothing today, solar and wind power will together generate 31% of electricity in 2050, by far exceeding hydropower – today's leading source of renewable power in the region. In addition to standalone solar, we foresee about 4% of total electricity generation in the region coming from solar combined with battery storage by 2050. Such early introduction of storage, given the low penetration of renewable energy that will be achieved by mid-century, is due to poor transmission, distribution infrastructure, and connectivity.

FIGURE 8.6.4

North East Eurasia grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

Looking at specific countries, Russia is making progress in solar energy, with notable projects like a large solar plant in Siberia and hybrid solar-diesel systems in Arctic regions, where it has been recently discovered that cold weather can, surprisingly, boost efficiency. Despite these efforts, the shift to renewable energy is slow, as solar power remains a small part of Russia's overall energy production. As Russia's energy policies continue to heavily favour fossil fuels over solar initiatives, its overall stance on renewable energy remains cautious.

Kazakhstan has recently advanced its solar energy sector substantially. A competitive auction system has been crucial to attracting investments, leading to the award of 440 MW in renewable energy projects in 2022, with solar energy playing a central role. International support, particularly from the European Bank for Reconstruction and Development (EBRD), has been pivotal in these developments. The government is also prioritizing small-scale solar projects, especially in remote areas, although low energy tariffs pose challenges for broader adoption. Despite these obstacles, Kazakhstan remains committed to its 2060 decarbonization goal, which includes a significant expansion of solar energy.

Despite the ongoing war, Ukraine has advanced most out of all countries in the region. In fact, the many damages incurred by the war in the country's energy infrastructure, to both power plants and grids, have triggered substantial rebuilding efforts. Solar power has been a particular focus here since it is crucial for stabilizing the energy supply in areas where traditional infrastructure has been destroyed. In August 2024, the Ukrainian government approved its *National Renewable Energy Action Plan* until 2030 (Sysoiev, 2024), which sets targets of increasing solar power capacity from 7.3 GW to 12.2 GW, onshore wind capacity from 0.5 GW to 6.2 GW and bioenergy facilities (biomass and biogas) from 0.3 GW to 0.9 GW. However, a recent report by Greenpeace (Bilek et al., 2024) suggests that Ukraine could install up to 14 GW of solar capacity by 2030, which still represents the lower bound of possible installations. The solar projects in Ukraine are being actively backed up by financing from the EBRD. Moreover, the country's integration into the European electricity network unleashes further opportunities for exporting solar energy to the EU.

Hydrocarbons: Re-routing eastward, but holding the energy transition back

The future of the region's energy exports and production is closely tied to its oil, gas, and coal exports. Currently, over a third of its fossil fuel production is exported, including 40% of its coal, 46% of its oil, and 24% of its gas. Historically, Europe (the EU) has been the primary market for Russian gas, largely transported via pipelines. However, following the onset of the war in Ukraine, Russia ceased gas supplies to the EU, causing a dramatic drop in pipeline exports from 140 billion cubic metres in 2021 to 63 billion cubic metres in 2022, and further to approximately 27 billion cubic metres in 2023. By 2023, exports to Europe (including Turkey) still made up just under half of Russia's gas exports. However, the outlook for Russian pipeline gas exports to the EU is bleak, as the European Commission aims to end these imports by 2027. The 81% decline in EU pipeline gas imports from 2021 to 2023 suggests that this goal is achievable.

In response, Russia is shifting its gas strategy toward two main areas: Pipeline exports to non-EU markets (primarily China, but also Turkey and former Soviet Union states) and liquefied natural gas (LNG) exports. Notably, in 2023, gas exports to China via the Power of Siberia 1 pipeline surged by more than 50%. Meanwhile, Russian LNG exports have remained relatively stable, partly due to extensive maintenance at the Sakhalin-2 and Yamal LNG facilities in 2023. Although around half of this LNG currently goes to the EU, this is expected to change soon as EU nations continue efforts to ban Russian gas imports.

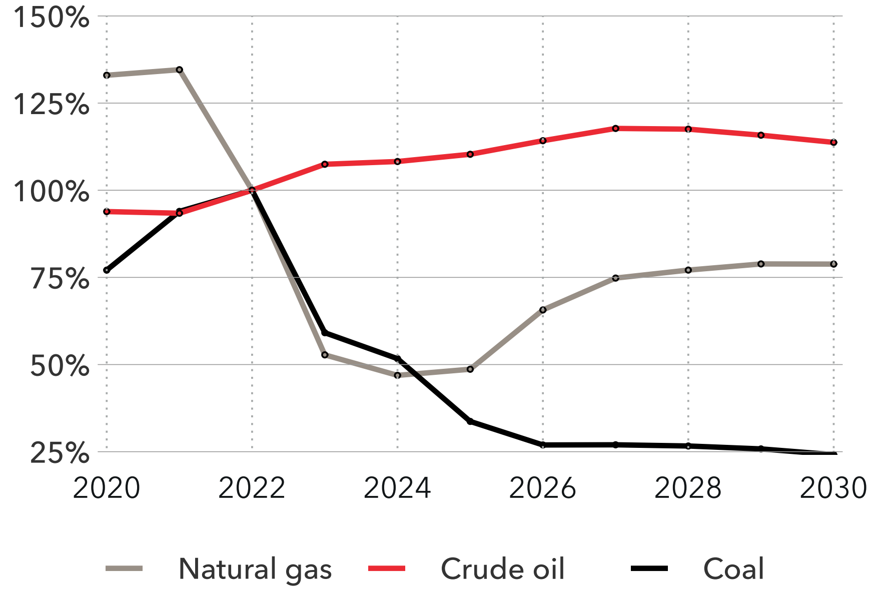
In addition, Japan reduced its LNG imports from Russia in 2023, driven by lower domestic demand.

Looking ahead, we anticipate that with the redirection of existing LNG flows (mainly to China) and the potential expansion of pipeline capacity (such as the Power of Siberia 2), Russia's gas exports will recover by the early 2030s (Figure 8.6.5), though they will remain below pre-invasion levels, reaching approximately 424 billion cubic metres by 2050. Domestic demand will not fully offset the decline in exports, with regional gas production, which peaked at 1,041 billion cubic metres in 2021, projected to decrease by 13% to 800 billion cubic metres by 2030. Export revenues are unlikely to return to pre-war levels due to higher transportation costs from longer routes and the need to sell eastward exports at a discount.

FIGURE 8.6.5

North East Eurasia fossil energy net exports, 2020 to 2030

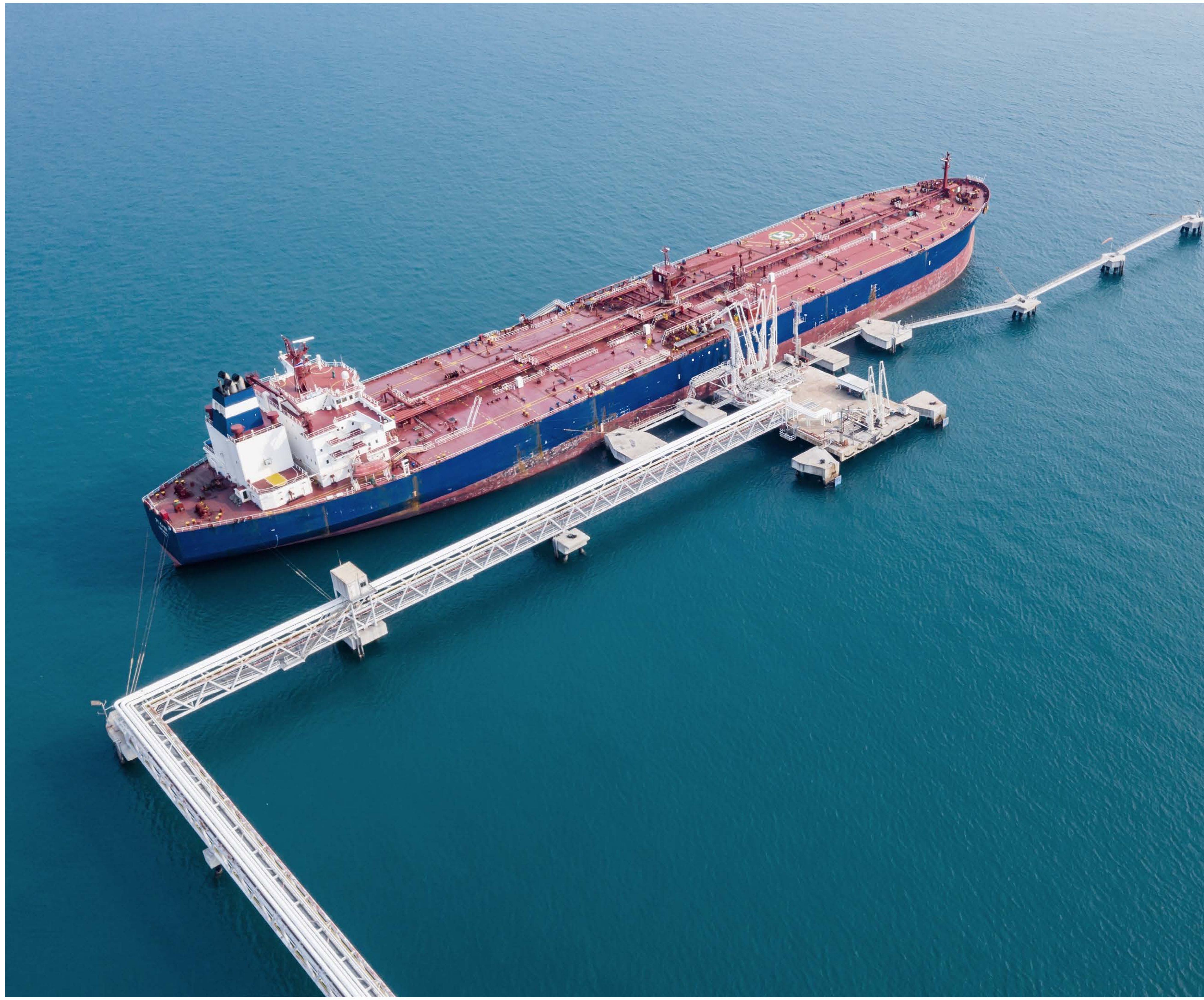
Units: Percentages, relative to 2022



Despite the EU's ban on seaborne crude oil imports from Russia and the G7's price cap on Russian oil products, Russia's oil exports have adapted more effectively than its gas exports. Russian oil continues to reach Asian markets via seaports, albeit at discounted prices and higher transportation costs due to longer routes. China remains the largest buyer of Russian crude (around 45%), followed by India (approximately 33%). Oil exports have already returned to pre-war levels and are expected to increase by 20% over the next five years.

In contrast, we expect coal exports to decline by 80% from 2021 levels towards 2030, showing a gradual increase only in the late 2030s to early 2050s, before eventually falling to about 13% of current levels by 2050. This trend reflects the anticipated long-term decline in coal demand from China, India, and South East Asia, which are currently Russia's primary coal buyers.

Unlike natural gas, oil and coal exports are easier to redirect as they can be more readily transported by sea. While oil is often transported via pipelines, it can also be moved cost-effectively by trains and trucks over land. However, long-distance transport from the region requires significant infrastructure. Exporting oil and coal overseas introduces additional complexities, such as the need for ships, which are subject to sanctions against Russia. Moreover,



insurers, particularly those in the West, are obliged to adhere to these sanctions, making it difficult for even non-Western ships to operate in this trade. The continued seaborne oil and coal exports from the region may be explained by the growing market share of non-Western insurers or by ships operating without insurance. Despite Russia's current ability to find buyers for its oil, it is likely being sold at a discount to Brent benchmark prices; from January 2024, the Urals/Brent differential has shrunk gradually from the USD 16 to 17 reached in 2022 and is now around USD 1. Furthermore, Russia's aggression against Ukraine poses substantial risks to the region's economic future.

Lastly, North East Eurasia will comprise about 5.2% of global demand for hydrogen and its derivatives and roughly the same in the corresponding global production by 2050. About 34% of this will be for production of ammonia, mostly as a feedstock and not as an energy carrier. While about 12% of regional hydrogen production will come from grid-connected electrolysis, the majority will be produced via fossil-based routes (including coal gasification), although abated with CCS. Most of the produced hydrogen and derivatives will be consumed within the region, but we foresee some small exports to China and South East Asia (less than 1 MtH_2 combined).

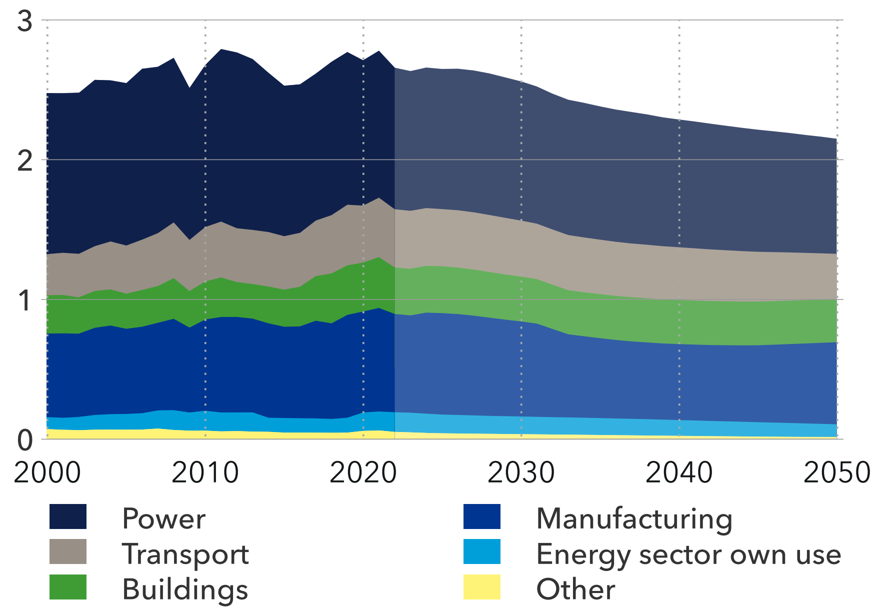
Emissions

Our projections indicate that the regional average carbon price will be USD 6 per tonne of CO_2 by 2030, rising to USD 20 per tonne by 2050. The slow pace of adoption and the region's low carbon prices –the lowest among all ETO regions – are key factors behind these estimates (Section 6.3). As a result, energy-related CO_2 emissions in North East Eurasia are expected to decrease by only 19% by mid-century compared to current levels, making it the industrialized region with the smallest reduction in emissions. This decline will be uneven across sectors (Figure 8.6.6). The largest reduction (22%) is expected in the transport sector; almost entirely from road transport due to the increasing share of electric vehicles in the total vehicle fleet (from zero now to close to 14% by 2050). This is followed by an 18% decrease in the power sector due to a greater share of renewables, and a 14% reduction in manufacturing. The buildings sector will see only an 8% decrease in emissions. By 2050, the region's total CO_2 emissions, including non-energy process emissions, are projected to reach 2.1 Gt, resulting in the highest per capita emissions of any region.

FIGURE 8.6.6

North East Eurasia energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Historical data source: IEA WEB (2024)

While other regions are experiencing strong electrification and a significant greening of their electricity sectors, such progress is relatively weak in North East Eurasia. Electricity demand will increase compared to other energy carriers but will still only account for 18% of total energy demand in 2050, up from 13% today. The use of natural gas in power generation will decline from 45% to 35% but will still represent the largest share of the energy mix. Coal will remain part of the power generation mix, but its share will drop significantly, from 19% today to just 3% by mid-century. Low carbon prices will impede the adoption of CCS technologies, so apart from limited use in ammonia and hydrogen production, less than 1% of emissions from the manufacturing and power sectors will be captured by 2050.

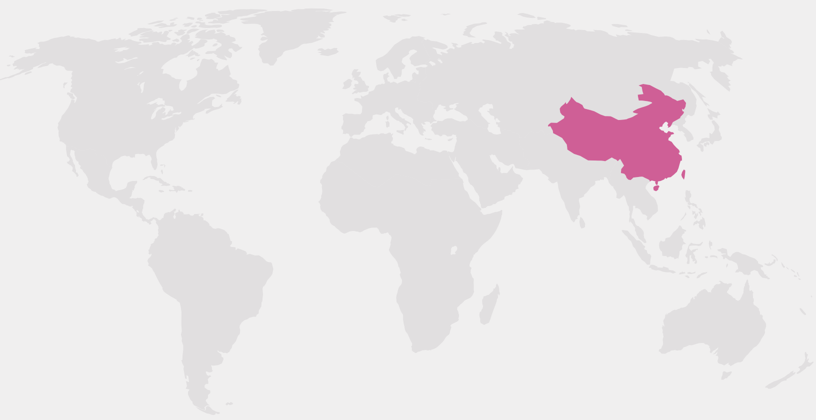
In terms of global climate policy, our analysis of country NDC pledges suggests that the region targets a 26% reduction in energy-related emissions by 2030 relative to 1990 levels. With energy-related CO_2 emissions projected to decrease by 40% after accounting for CCS, the region is on track to meet its climate goals ahead of the target year. However, the collapse of the Soviet Union in 1991 complicates emission statistics, as they show a 40% reduction in emissions between 1990 and 1997. While industrial output fell by half during that period, these statistics may overstate the actual decline in emissions. Nonetheless, the reported increase in emissions between 1997 and 2020 appears reliable. North East Eurasia sees the lowest reduction in emissions of any industrialized region with a decrease of 19% in CO_2 emissions between 2023 and 2050.

This means that 2060 carbon neutrality commitments have low likelihood of being met. On the other hand, in efforts to rebuild its energy sector, Ukraine will look to align itself with the EU's *Green New Deal* policies and is likely to prioritize renewables as a cleaner and more secure energy sources, which could positively influence the region's overall energy mix.

> While other regions are experiencing strong electrification and significant greening of their electricity, such progress is relatively weak in North East Eurasia.

8.7 GREATER CHINA (CHN)

This region consists of Mainland China, Hong Kong, Macau, and Taiwan.



	Population (Billion)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/person (tonnes)
2023	1.45	34.7 24 000	168 116	11 7.7
2050	1.34	64.1 48 000	142 106	3 2.5

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.7 GREATER CHINA (CHN)

Current position

China's policymaking (environment-energy-industrial) is heavily centralized with top leadership setting the direction for R&D, sector investments, and development of industrial clusters. Five-year planning steers the transition and state-owned enterprises are instruments to realize strategic goals.

Globally, China expands energy, infrastructure, and resource projects through the *Belt and Road Initiative* (BRI) in cooperation agreements with more than 150 countries.

The government has an around 5% annual economic growth target and relies heavily on a production-intensive stimulus approach to achieve economic goals. Cleantech industries are key propellors of growth.

China invested an estimated 6.3trn yuan (USD 890bn) in clean-energy sectors in 2023, a 40% increase from 2022 (Myllyvirta, 2024) and China accounts for one-third of clean-energy investments worldwide (IEA, 2024a).

China's population has peaked, but energy demand is still growing. Hydrocarbons remain prominent accounting for 86% of primary energy supply in 2023. Chinese emissions set new global records in 2023, with coal consumption ticking up mainly to cope with hydropower shortage, though emissions show signs of flattening.

The government is committed to dual carbon goals – peaking emissions before 2030 and achieving carbon neutrality before 2060. Decarbonization occurs in balance with overriding economic development, price stability, and energy security goals. The latter explains ramp up in hydrocarbon exploration (Xu, 2024) and approvals of new coal-fired and nuclear plants to guarantee supply.

Worsening weather extremes range from record-breaking heat and drought to the heaviest rains and floods (MEE, 2023). Spring 2024 floods from heavy rains in several Chinese provinces, such as Guangdong and Fujian, resulted in financial losses of at least USD 5bn (Munich RE, 2024).

Pointers to the future

- China's policies seek to boost economic autonomy and resilience to market dynamics and trade tensions. Economic ties will be enhanced worldwide to reduce dependence on the European and US markets, and as outlets for excess cleantech manufacturing capacity.
- China sees decarbonization and clean energy industries as the future growth engine. Industrial capabilities and manufacturing that have environmental advantages and low-carbon development as a strategic direction will enjoy preferential government policy and support. The 2023 updated *Catalogue for Guiding Industry Restructuring* will align investors with national aspirations and signals a strategic shift to high-tech industries and environmental priorities.
- The central government aims to rebalance the economy towards domestic consumption and high-quality production for a rising share in medium- and high-tech products, thereby adjusting the economy and manufacturing from high- to low-energy intensity.
- China's policy breadth will continue to be inclusive of mandatory energy conservation targets, fossil-fuel consumption controls non-fossil energy increases, compulsory procurement and clean energy obligations combined with tradeable green certificates and carbon pricing.
- Supply-sector policies will favour renewable electricity, flexibility sources, green hydrogen, and hydrogen derivatives. CCUS policy and support for its large-scale application appear at the tail end of the transition.
- Demand-sector policies will focus primarily on improving energy consumption patterns and switching end-use demand from combustion of fossil fuels to increased renewable energy use and hydrogen.
- The *15th FYP* period (2026-2030) will gradually establish a 'dual carbon control' system for carbon emissions that will limit carbon intensity and total emissions (State Council, 2024).

Energy transition: an immense shift sullied by coal

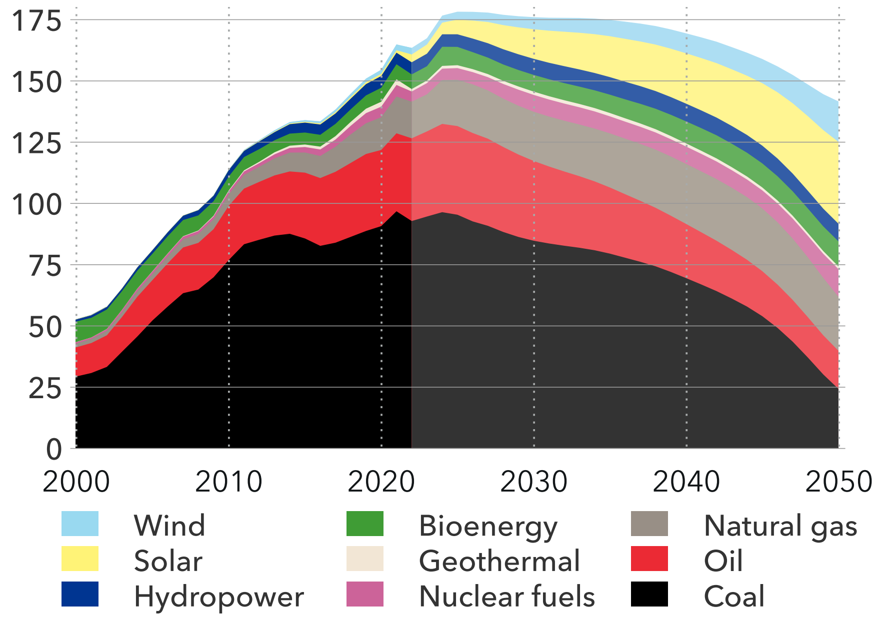
In 2023, China accounted for 17.8 % of the world population and 21% of global GDP. Energy demand, closely correlated with both population and economic growth, has soared – China now accounts for 26% of global primary energy demand. China is responsible for a third of global energy-related CO_2 emissions, so developments there are crucial for the world meeting its emissions-reduction target and climate objectives.

China's primary energy supply nearly tripled over the last two decades (Figure 8.7.1). The strong increase came from coal, which in 2023 accounted for 57% of primary energy use in China and 59% of global coal consumption. China's energy use started to diversify in 2013, with strong growth in natural gas, hydropower, nuclear, solar PV, and wind. There will be very marginal upticks in coal and oil use in the next couple of years, before they steadily decline to one third and half, respectively, of their current volumes by 2050.

FIGURE 8.7.1

Greater China primary energy consumption by source

Units: EJ/yr



Historical data source: IEA WEB (2024)

The forecast energy supply and demand trends in the coming decades are influenced by government energy and environmental policy and are closely linked to the region's energy efficiency, demographic, and economic developments. Average annual economic growth has exceeded 8% for 30 years, with GDP per capita increasing tenfold in the same period. However, we expect this to slow significantly over the next 30 years to an average of 2.3% growth, due to population reduction, demographic shifts, and China's transition to a more mature economy, with fewer productivity gains in industry. Over time, its long-term economic growth rate will resemble that of other medium and high-income countries. By 2050, GDP per capita is projected to double its current value, reaching USD 48,000 per year. Increased energy efficiency, along with reduced population and GDP growth, will see China's energy use peaking at around 178 EJ in 2030, plateauing for about five years, and then gradually reducing to 142 EJ by mid-century.

In April 2024, DNV published standalone *Energy Transition Outlook China 2024.* That comprehensive Outlook, running to over 100 pages, was based on our ETO 2023 forecast. Our 2024 forecast includes updated figures for China, with only minor changes in most areas.

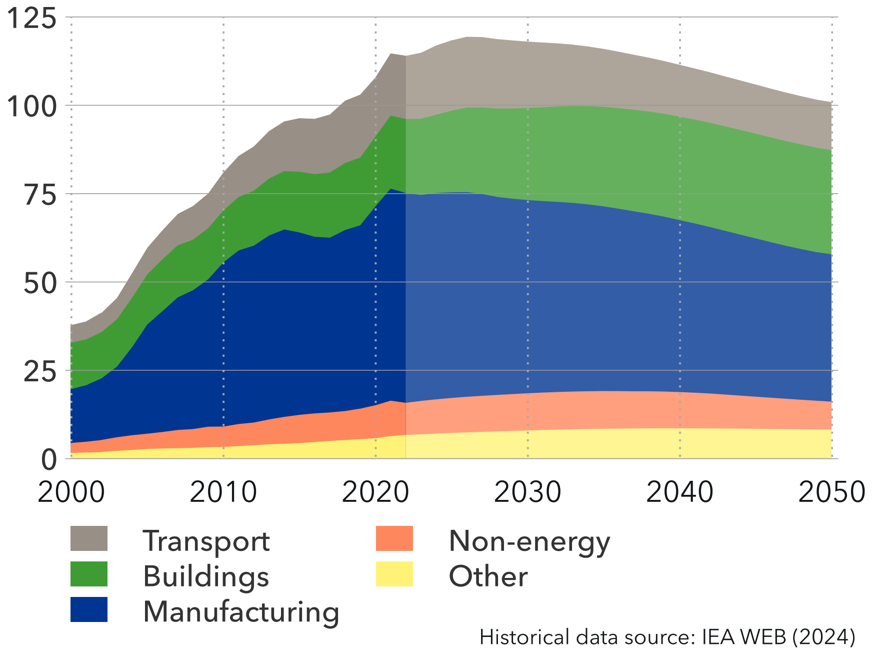
Energy demand levelling off

From 2022 to 2023, the energy demand growth rate was twice what it was from 2021 to 2022 due to a post-pandemic rebound in economic activity. As a result, China set new records for emissions. Final energy use is projected to grow 5% to peak at 119 EJ in 2027, plateau for a decade, then decline to 101 EJ by 2050. This plateau and decline are due to demographic shifts, reduced reliance on heavy industry, increased energy efficiency, and slower economic growth.

FIGURE 8.7.2

Greater China final energy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2024)

Figure 8.7.2 shows the final energy demand by sector. By 2050, manufacturing will still be the largest sector of energy demand with a 41% share, down from 51% today, while the share of buildings will grow from 19% to 29%. Transport will slowly decline from its present 16% to a 13% share in 2050, as electrification of road transport scales from the late 2020s.

Please refer to DNV's [Energy Transition Outlook China 2024](#) for an in-depth study of China's transition (DNV, 2024).

Manufacturing stays big, but heavy industry reduces

Manufacturing is the largest consumer of China’s energy, accounting for 51% in 2023, driven by industries like iron and steel, cement, and base materials. This sector's dominance highlights China's role as the ‘factory of the world’, contributing to over 40% of global manufacturing energy demand. While heavy industries have been pivotal, the sector is evolving towards high-tech, advanced manufacturing. Despite this shift, manufacturing is projected to remain the largest energy consumer by 2050, with a 41% share. The growth in manufacturing has historically been supported by intensive coal use. Coal provided more than 80% of manufacturing energy over the last two decades, if accounting for both direct and indirect (share of coal in electricity) energy use (Figure 8.7.3). The share of coal is now progressively declining as heavy industries become less important. Coal’s share of manufacturing energy demand will fall to about a third to 2050.

Buildings electrifying

China has prioritized energy saving in buildings and green building development in its *14th Five-Year Plan*. While there will be improvements in energy efficiency, insulation, and heating/cooling equipment, the energy demand of buildings is still set to increase as GDP continues to rise, driving the amount of floor area in both residential and commercial buildings to rise. The buildings energy demand in China is projected to grow by approximately 37% to 29 EJ by 2040, after which it will plateau until mid-century. As it is shown in Figure 8.7.4, the share of electricity will increase from the current 37% to 65% by mid-century, helped by continued urbanization.

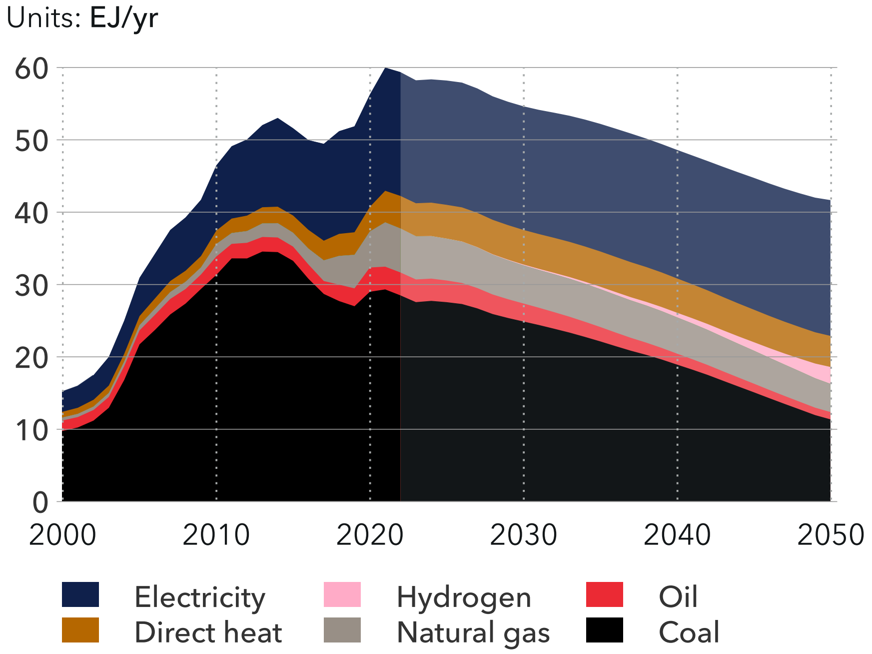
Figure 8.7.5 shows buildings energy demand by end use. While energy demand for heating will remain relatively stable, the demand for water heating and cooking will slightly decrease. Conversely, we expect the demand for cooling to increase from 1.8 EJ to 8.3 EJ over the next 20 years; by 2050, it will represent 28% of Chinese buildings energy use, just behind energy needs for heating, which will account for 30%. This surge in cooling demand is driven by urbanization and a wealthier population, but also by rising global temperatures, as measured by the 40% increase in cooling-degree days.

Transport

We anticipate passenger flights will triple, rail freight and passenger numbers will double, and vehicle fleets will expand by an anticipated 18% between 2023 and 2050. In 2023, transport consumed 19 EJ of energy, representing 16% of China’s energy demand. Despite the increased activity expected in 2050, energy consumption in the sector is projected to reduce to 14 EJ by mid-century, representing 14% of demand. This reduction primarily stems from substantial efficiency gains achieved through the

FIGURE 8.7.3

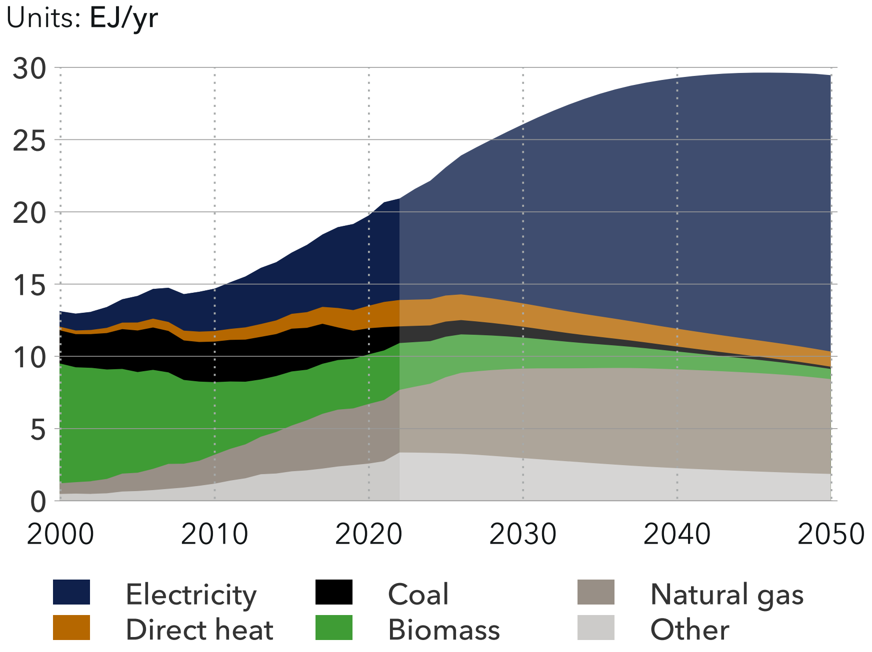
Greater China manufacturing energy demand by carrier



Historical data source: IEA WEB (2024)

FIGURE 8.7.4

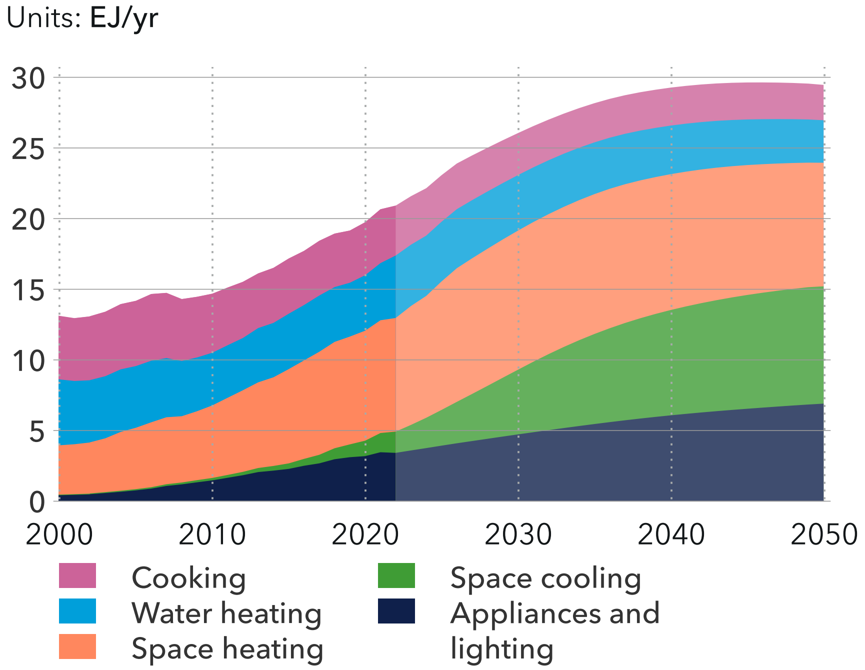
Greater China buildings energy demand by carrier



Historical data source: IEA WEB (2024)

FIGURE 8.7.5

Greater China buildings energy demand by end-use



Historical data source: IEA WEB (2024), EIA RECS (2020), DNV analysis

widespread electrification of road transport. Figure 8.7.6 shows transport energy demand by subsector and energy carrier.

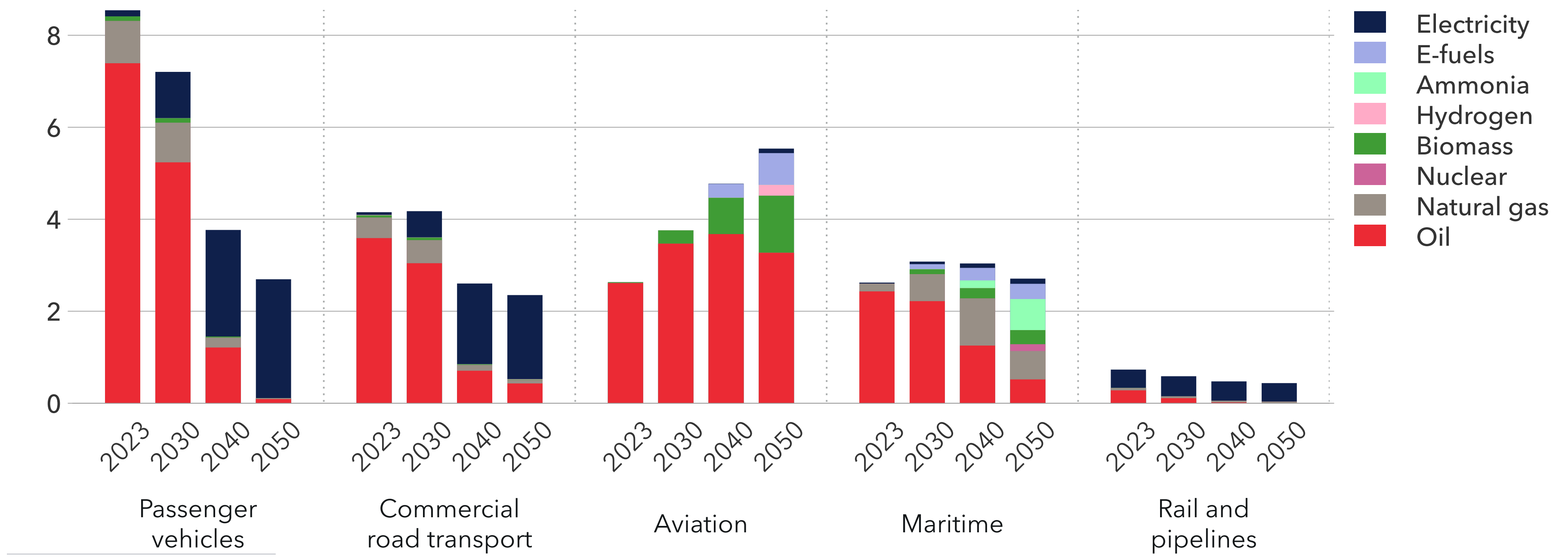
China is solidifying its leadership in the global EV and EV battery markets, driven by robust domestic production and a significant share of global exports (IEA, 2024b; SNE, 2024). As of 2023, Chinese manufacturers dominated the global EV battery market, with CATL and BYD accounting for 27% and 16% respectively, and other Chinese companies contributing around 10%. These firms have not only led in battery production but also become pivotal in the global supply chain as the demand for EVs continues to surge. In 2023, China's share in the global battery electric vehicle (BEV) market was 30%, and BYD outsold Tesla as the global number one EV producer in the final quarter of 2023.

Energy demand in the road sector, currently at 13 EJ, will increase by 2% in the next two years, before reducing to 5 EJ in 2050. During this period, the share of electricity in the road sector is projected to rise dramatically from 2% to 88%. In 2023, BEV and plug-in hybrid electric vehicles (PHEV) made up about 25% and 14% of passenger and commercial vehicle sales, respectively. We expect this share to exceed 50% in 2026 for passenger vehicles.

FIGURE 8.7.6

Greater China transport energy demand by subsector and carrier

Units: EJ/yr



In 2030, our projections indicate that 90% of passenger vehicles, 65% of commercial vehicles, and 98% of two- and three-wheelers will be electric. Our forecast shows substantial growth in the density of passenger vehicles, potentially peaking before 2040 at about 420 million vehicles, a 56% increase from 2023. However, in the 2040s, factors such as a declining population, greater automation, and increased car sharing are expected to reduce the number of vehicles. China also has goals for hydrogen-powered passenger and commercial vehicles. As detailed in Chapter 1 of our Outlook, our modelling currently indicates that hydrogen cannot compete with EV in passenger vehicles or commercial vehicles.

Energy demand in the maritime sector in 2023 was about 2.6 EJ. We expect this demand to peak at the beginning of 2030 at 3.1 EJ before declining to present levels by mid-century. During this period, the energy mix will undergo significant changes with biofuels and low carbon fuels from hydrogen derivatives entering and the share of fossil fuels decreasing from 99% to 42%.

China's economic progress, with a rising middle class increasingly opting for air travel, is likely to drive a tripling of energy demand in aviation through to 2050, reaching 1.6 billion passenger trips/yr by mid-century. Despite the tripling of passenger flights, aviation sector emissions in China by 2050 will be only 17% higher than in 2023. Switching to low-carbon fuels plays a critical role. In 2023, energy demand in aviation was primarily met by oil (99%) and biofuel. By mid-century, we project energy demand will reach 5.5 EJ, with oil still dominating the mix at 60%, while the remaining demand will be met by bioenergy (22%), e-fuels (13%), hydrogen (4%), and electricity (2%).

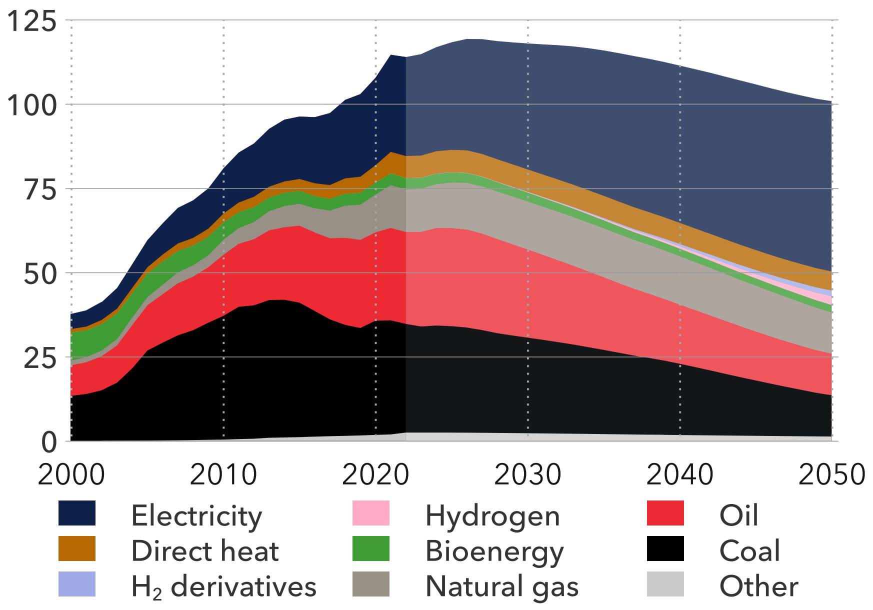
Electricity growing in all sectors

While demographics and economics significantly influence energy consumption, Chinese policy is the most crucial factor shaping the energy mix. Electrification of energy demand sectors is a key strategy to enhance energy efficiency and reduce emissions. Additionally, increasing electrification with power produced from non-fossil sources enhances China's energy independence and security. As Figure 8.7.7

FIGURE 8.7.7

Greater China final energy demand by carrier

Units: EJ/yr



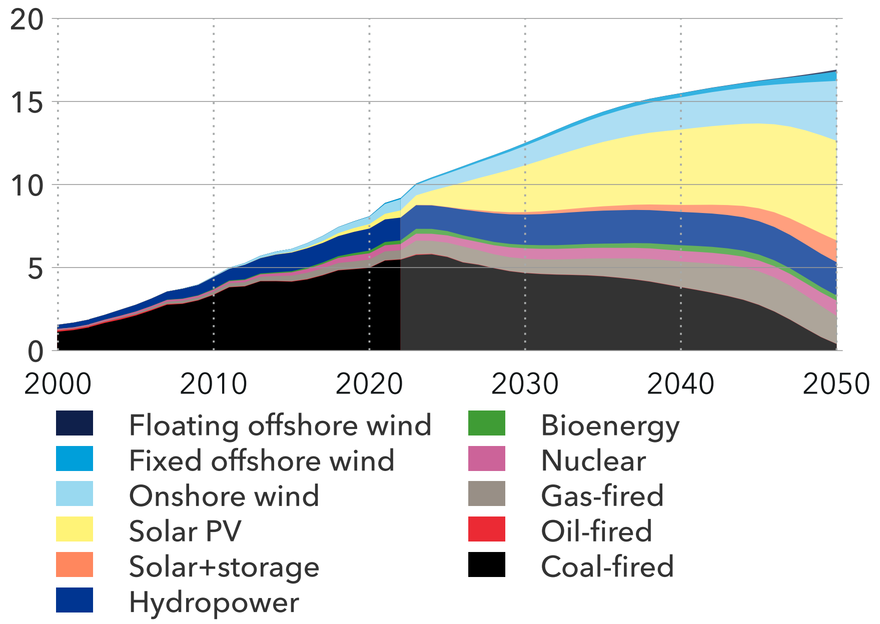
Historical data source: IEA WEB (2024)

shows, direct use of fossil fuels met 63% of the final energy demand in 2023, but the share of fossils was significantly higher than that, given that about 57% of 2023's grid-connected electricity was from coal and 7% from gas. By 2050, excluding the remaining 12% fossil fuel share in the power mix, the fossil share in the final energy demand will be 36%, with almost equal share for coal, oil, and gas. The share of electricity is projected to increase to 50% by 2050. Hydrogen is negligible as an energy carrier today, but will start to replace some coal and gas demand in manufacturing in the 2030s and its share will rise to 2.6% in 2050. In the 2040s, we will see the uptake of ammonia and methanol in shipping and e-fuels in aviation which will account for 2% of demand in 2050.

FIGURE 8.7.8

Greater China grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

Decarbonizing electricity supply

In 2023, clean power made up 35% of China's electricity mix, with hydro at 14% and wind and solar reaching a record 14%. China's annual electricity production will increase by 70% to reach 17 PWh in 2050. Coal's share of China's energy mix has already decreased from 73% a decade ago to 57% today and is projected to further decline to 37% by 2030 and just 2% by 2050 (Figure 8.7.8). By mid-century, we expect gas will maintain a minor share of 10%, while oil becomes negligible, resulting in only 12% of China's electricity remaining reliant on fossil fuels. In contrast, the shares of solar and wind will reach 43% and 26%, respectively, by 2050.

We expect grid-connected solar PV capacity to reach 2,170 GW and off-grid capacity (for green hydrogen production) to reach 70 GW by 2030, and further increase to 4,900 and 1,100 GW, respectively, by 2050. Similarly, by 2030 grid-connected installed wind capacity will be 700 GW, 90% of which will be onshore wind. By mid-century, we expect onshore wind to grow to 1920 GW grid-connected and 110 GW off-grid. Offshore wind installations, which are all grid-connected, will have a capacity of 200 GW fixed offshore and 45 GW floating offshore by 2050.

Hydropower is also large in China, producing 1.4 PWh/yr, a figure that will grow 42% over the next decade and thereafter stabilize. With a share of 13% in 2023 and 12% in 2050 of the total electricity mix, this dispatchable renewable energy source is crucial to balance the variable renewable production from solar PV and wind.

While nuclear power station costs in China are lower than those in OECD countries, they remain more capital-intensive compared with other plant types. Nevertheless, China, driven by energy security policies, is committed to further enhancing its nuclear share in power production. In 2023, nuclear power accounted for about 4% of the country's electricity mix, producing approximately 430 TWh/yr. Nuclear has gained momentum in last the half decade. For the years 2019 to 2024, the number of nuclear power units approved in China was 6, 4, 5, 10, 10, and 11 respectively (Zhu, 2024). Looking ahead, China's nuclear capacity and production are projected to increase fourfold, reaching 920 TWh/yr by 2050, which would constitute 5% of the Chinese electricity mix. While China is the fastest-expanding nuclear power generator in the world, the exponential growth of solar and wind serves to keep the nuclear share of the power mix pretty much constant.

Over the past decade, China has accounted for more than a third of the world's transmission grid expansion. However, despite these advancements, China faces significant gridlock issues as it rapidly expands its renewable energy capacity. These problems are exacerbated by regional imbalances where renewable energy production does not match consumption patterns, leading to curtailments when local demand is insufficient. The government has committed USD 800bn over six years to upgrade the transmission network, aiming to enhance long-distance transmission capabilities and improve coordination of power generation across provinces (White, 2024).

A small but important role for hydrogen

China predominantly generated hydrogen through fossil value chains in the last two decades. Despite its comparatively high cost, hydrogen and its derivatives will play a small, albeit important, part in China's energy system. By 2050, the share of hydrogen and derivatives, such as e-fuels and ammonia, in China's final energy demand will reach 4.5%. This amounts to 21 Mt added to the continued need of 39 Mt for feedstock. By mid-century, 60% of produced hydrogen (for both feedstock and as energy carrier) is green. Most of this is from dedicated solar, while 15% is blue from fossil fuels with CCS and only 25% comes from fossil fuels without CCS.

Imported oil and gas prevents energy independence

Energy security and independence is a top priority for China. In our *ETO 2024 China* report, launched in April 2024, we highlighted that China will only partially achieve energy independence by 2050. While coal and non-fossil energy sources like nuclear, bioenergy, and renewables are primarily developed domestically, China will continue to rely heavily on imports for most of its oil and gas. To achieve full energy independence, China needs to expedite its transition from oil and natural gas.

In 2023, China produced 4.4 billion tonnes of coal, a 2.9% increase compared to the previous year. The coal demand was so high that the country had to import an additional 420 million tonnes to meet the demand. We forecast that coal production will start to decline from 2025 and gradually reduce to 80%

of current levels by 2035 and 25 % of current levels by 2050.

The Chinese government is also focusing on enhancing the efficiency and safety of its coal industry by closing smaller, less efficient mines and concentrating production on the largest and most advanced ones. This structural reform aims to optimize production capacity and increase the proportion of advanced coal production. Furthermore, China is developing a 'coal capacity reserve system' that can supply up to 300 million tonnes per year to handle extreme situations such as severe weather or fluctuations in international energy markets (Kemp, 2024).

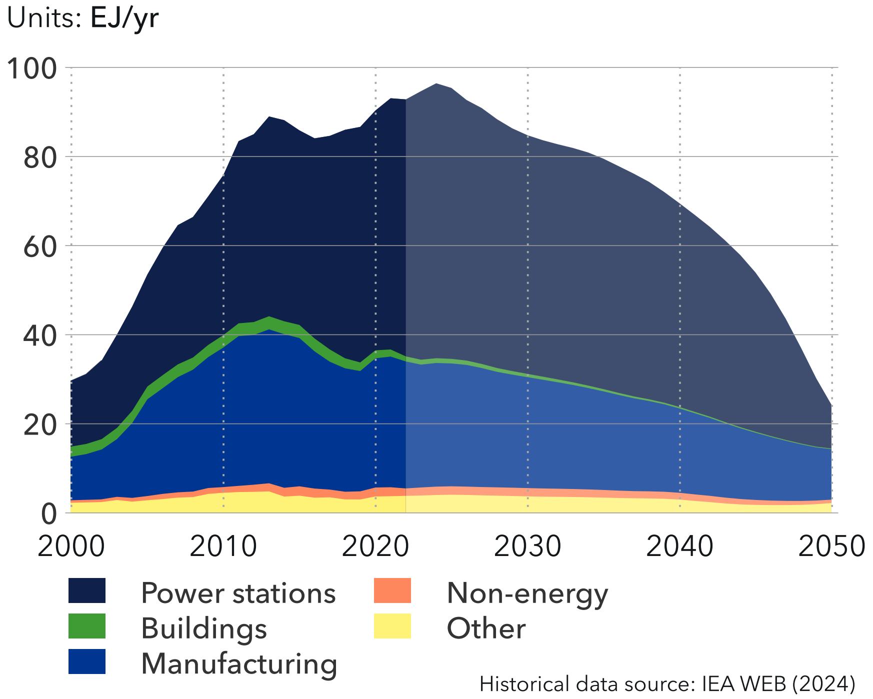
Figure 8.7.9 illustrates coal demand across various sectors, highlighting that the power generation and manufacturing sectors are the primary coal consumers in Greater China.

China achieved record-breaking crude oil and natural gas production in 2023, with unconventional gas contributing significantly to the overall figures. At the same time, the region's oil demand reached a record 16 Mb/d, up 5% from the previous year. The country also imported a record 11.3 Mb/d of crude oil, a 10% increase, with Russia and Saudi Arabia as the largest suppliers. Although oil demand is projected to fall after 2025 due to road transport electrification, China will still need 7.7 Mb/d by 2050. With current reserves, China can only produce 0.8 Mb/d, indicating continued heavy reliance on imports. Figure 8.7.10 shows that, while transportation currently accounts for 58% of oil demand, we expect this to decrease to 35% by 2050, with plastic production surpassing transportation by 2040 and reaching 45% by 2050.

In 2023, China's natural gas demand was approximately 540 Bcm per year. The country imported around 190 Bcm via LNG and 50 Bcm via pipelines. We project natural gas will increase to 797 Bcm by 2045 before gradually reducing to 680 Bcm by 2050. Based on current gas reserve exploration, China will still need to import 370 Bcm to meet its demand in 2050. Figure 8.7.11 shows the historical and forecast trend for China's gas import via pipeline, dominated by North East Eurasia (mostly Russia) or as LNG, dominated by OECD Pacific and the Middle East and North Africa.

FIGURE 8.7.9

Greater China coal demand by sector



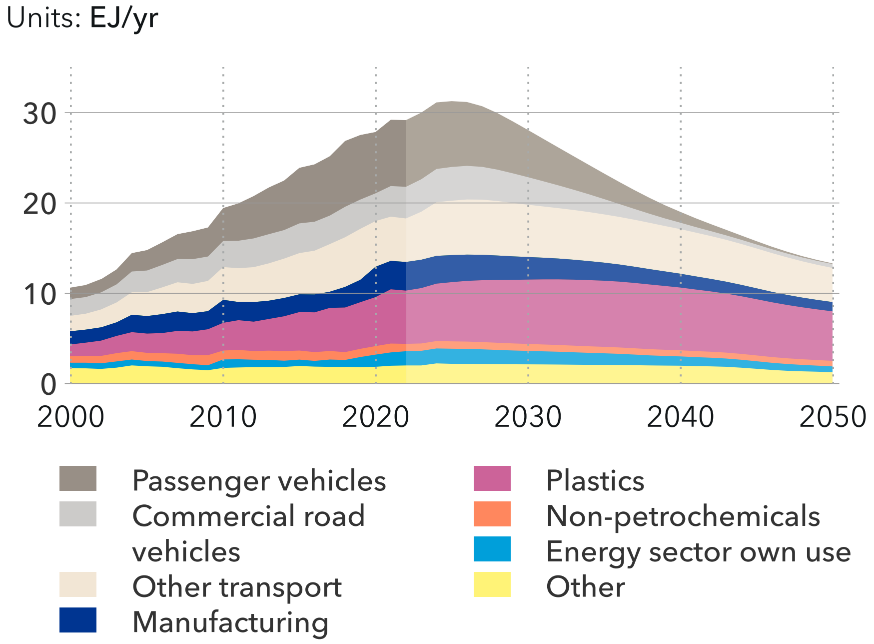
Historical data source: IEA WEB (2024)

Energy efficiency and peak energy

Improved energy efficiency is a cornerstone of China's energy and climate policies, and the targets in the last Five-Year Plans has largely been met. In the coming years, China's focus on energy intensity – defined as the amount of primary energy used per GDP unit – is expected to yield further significant reductions. We project the current rate of 4.8 Megajoules per US dollar (MJ/USD) to be 2.2 MJ/USD by 2050. However, this downward trend will moderate over time. The current annual decrease of 3% in energy intensity will likely to slow to 2% as 2050 approaches, partly because much of the effect of electrifying road transport will have been achieved by then. Figure 8.7.12 illustrates a broader transformation within China, marked by significant advancements in energy efficiency, a decline in GDP growth per capita, and a reducing population.

FIGURE 8.7.10

Greater China oil demand by sector



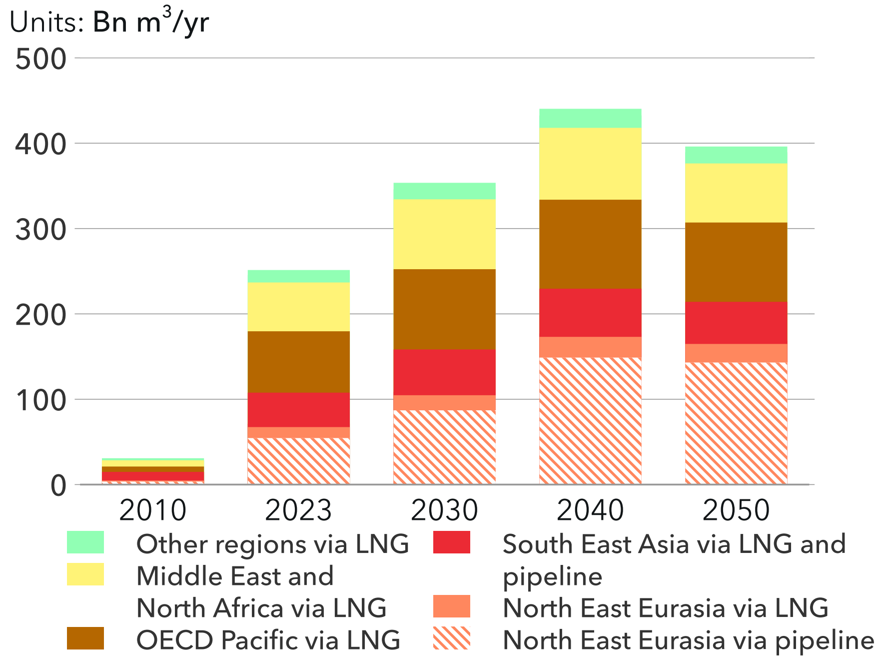
Historical data source: IEA WEB (2024)
Note: Non-petrochemicals includes bitumen, asphalt, and lubricants.

A modest role for carbon capture

CCS plays a small role in China today, with about 3.5 Mt being captured. However, policy support for CCS has also increased with its inclusion in China's 1+N climate framework, the *14th Five-Year Plan* (2021-2025), key projects for environmental protection and resource conservation, and in provincial decarbonization strategies. We forecast initial growth in

FIGURE 8.7.11

Greater China gas import from region via pipeline and LNG



CCS to be relatively low, reaching 50 $MtCO_2$/yr by 2035 dominated by hydrogen and e-fuel production (Figure 8.7.13). However, after 2045, CCS will grow much faster in the power and iron and steel sectors. Overall, CCS across all sectors will likely capture 330 $MtCO_2$/yr by 2050, at that time capturing almost 10% of emissions.

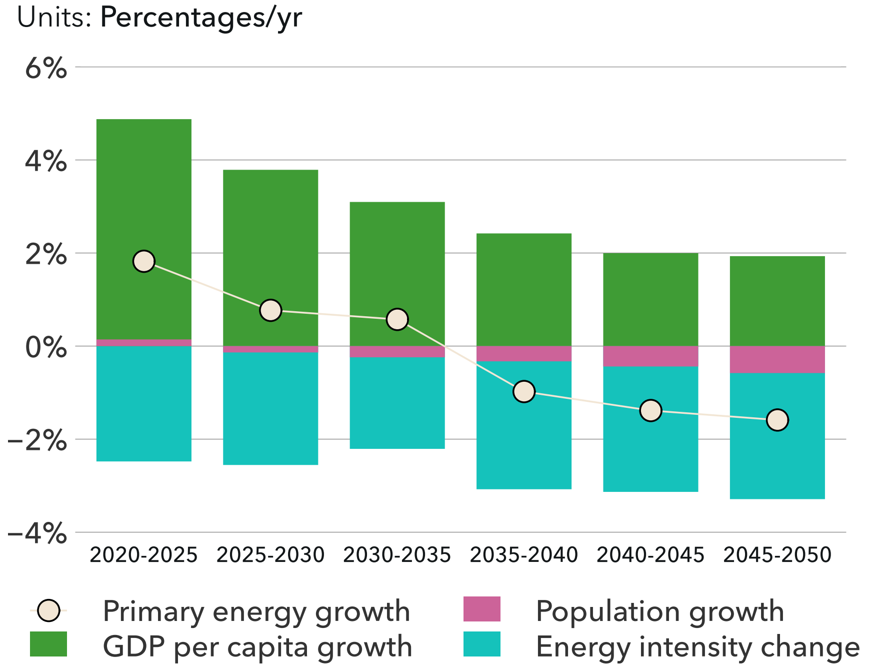
Negative emission technologies from bioenergy with BECCS and DAC will have a slow and very moderate development starting only in the mid-2040s and reaching 15 $MtCO_2$/yr by 2050.

Energy-related CO_2 emissions peak in 2024

China's most pronounced climate policy is its commitment for CO_2 emissions to peak before 2030, and to reach climate neutrality in 2060.

FIGURE 8.7.12

Greater China primary energy growth as a function of population, GDP/capita and energy intensity improvements

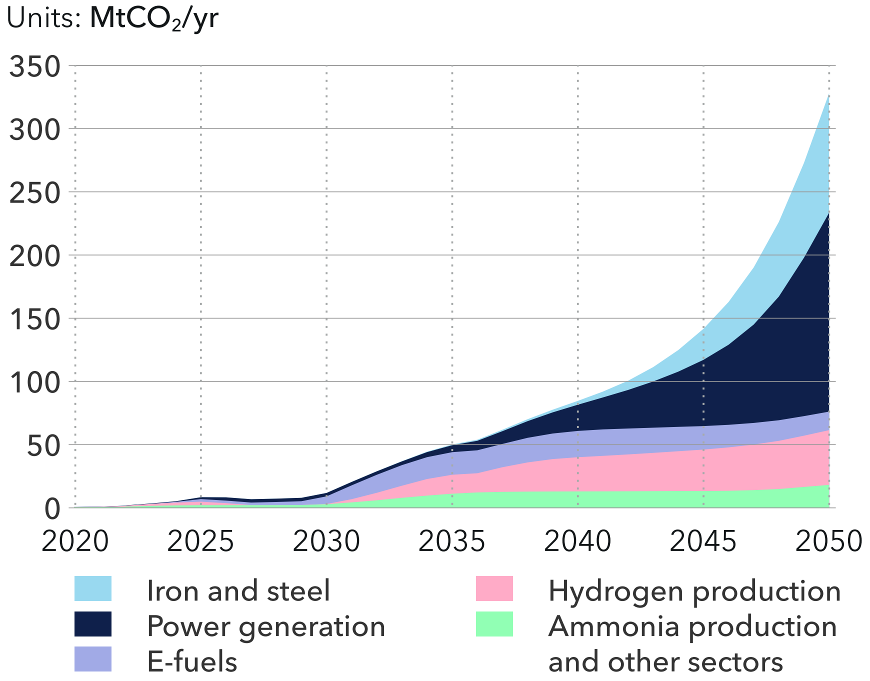


In 2023, China was responsible for 33% of global energy-related CO_2 emissions – 11 $GtCO_2$, with coal accounting for 75%of these emissions. The CO_2 emission trajectory follows fossil fuel combustion, and we therefore find peak CO_2 in 2024, before it gradually drops to 10 Gt in 2034 and further to 3 Gt in 2050.

Consequently, the carbon intensity of Chinese energy use reduces from 103 gCO_2/MJ to 33 gCO_2/MJ over the coming three decades and is coupled with the reduction in Chinese coal consumption.

FIGURE 8.7.13

Greater China CO_2 emissions captured by sector



China's target is to reduce carbon intensity (per unit of GDP) by 65% from 2005 levels by 2030; our Outlook suggests a reduction of 59% by then, indicating that this target will be missed.

Historically the power sector has had the highest emissions, followed by iron and steel production, other manufactured products, and transport (Figure 8.7.14). Transitioning from coal to renewable and nuclear energy for power generation, adopting electric arc furnaces (EAF) in iron and steel production, and replacing internal combustion engines with EVs in road transport will drastically reduce emissions in these sectors by 2050.

On top of energy-related emissions, process emissions of 1.6 $GtCO_2$ per year today are expected to fall to about 1.0 $GtCO_2$ per year in 2050.

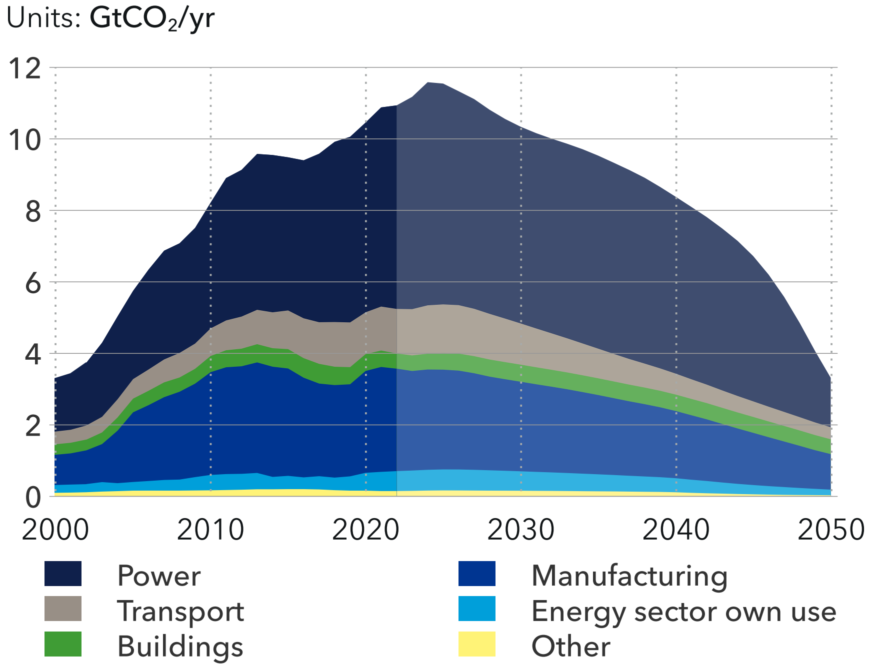
Our projection for China's average carbon-price level is USD 20/tCO_2 in 2030, USD 40/tCO_2 in 2040, and USD 90/tCO_2 by 2050, a level exceeded only by Europe and the OECD Pacific regions. The upward pricing trend is underpinned by the inclusion of more sectors and expanding coverage in China's national emissions trading scheme.

Comparing the DNV forecast with official Chinese goals and other Chinese forecasts, we find that China will meet the main target of peaking CO_2 emissions before 2030, unless we see a high level of Chinese AFOLU (agriculture, livestock, forestry, and other land uses) emissions, which is unlikely. China's high-level goal of carbon neutrality by 2060 cannot be read directly from our forecast, which stops in 2050. However, our forecast indicates that the 2060 target is likely to come close to being achieved, although some additional measures should be taken, especially in the manufacturing and process industries, to be on track for the 2060 goal.

> Oil demand is set to fall from 16 Mb/d in 2023, but China will still need 7.7 Mb/d in 2050.

FIGURE 8.7.14

Greater China energy-related CO_2 emissions by sector



Historical data source: IEA WEB (2024)

8.8 INDIAN SUBCONTINENT (IND)

This region consists of India, Pakistan, Afghanistan, Bangladesh, Sri Lanka, Nepal, Bhutan, and the Maldives.

India and Pakistan account for **80%** of region energy use.

	Population (Billion)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/ person (tonnes)
2023	1.92	16.4 8 500	54.2 28.3	3.1 1.6
2050	2.33	50.1 21 500	196.6 41.5	3.2 1.4

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.8 INDIAN SUBCONTINENT (IND)

Current position

Economies and energy demand are expanding with a demographic surge: India is the world's most populous country, Pakistan has the highest population growth rate in South Asia, and Bangladesh is among the most densely populated countries.

The Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation is a platform for regional cooperation (South- and South East Asia), connectivity and trade (Bhattacharjee, 2023). India boosts regional relations through its *Neighbourhood First Policy* with 50% of its soft lending going to neighbours (PRS, 2023).

Sri Lanka, Pakistan, and Bangladesh participate in China's *Belt and Road Initiative* (representing up to 30% of total external debts) and are under IMF financial assistance programmes for economic stabilization and reform to state-owned enterprises.

Energy supply is 76% (2023) fossil-fuel based with high import reliance and energy shortages in Bangladesh, Pakistan, and Sri Lanka. Pakistan announced Russian gas and crude oil imports, reportedly at a price point lower than Gulf region imports (Khan, 2023).

There is vast clean energy potential; India especially is making strides in renewable capacity additions, auctioning 20 GW in 2023.

CO_2 emissions are increasing, but some countries have a net-zero policy: Bhutan commits to remain carbon neutral, Maldives for 2030, Nepal for 2045, and notably India is targeting carbon neutrality by 2070 (Net Zero Tracker, 2024).

Climate risks range from sea-level rise and heat waves to abnormal precipitation; recent floods costing Pakistan USD 2.3bn worth of crop damage (Shehzad, 2023) and heat stress putting 4.5% of India's GDP at risk (Reserve Bank of India, 2023).

Pointers to the future

- Seizing the renewable energy opportunity to avoid development based on fossil fuels and heavy import bills is a predicament of the region.
- Decentralized renewables may enable more equitable sharing of economic benefits and are supportive of local industrialization. However, challenges need to be addressed, including the impacts large scale solar and wind farms have on agricultural land, the environmental impacts of hydropower dams, and the impact of the transition on coal-related jobs. (Mirza, 2023).
- India targets 50% generation capacity from non-fossil-fuel sources and meeting 50% of energy requirements from renewables by 2030. Planned tendering aims to add 50 GW renewable generation capacity annually to achieve 500 GW by 2030, supported by renewable purchase obligations mandated for 2029 or 2030. Ambitions for a global low-carbon hydrogen ecosystem (Chapter 6) will have a USD 1.5bn World Bank loan backing the push. Policies extend beyond the power sector, but anchoring domestic demand will be important for India's transition.
- Sri Lanka passed legislation (2024) to reform its power sector and attract renewable investments, targeting 70% renewable electricity by 2030. Pakistan aims to shift energy supply to 60% renewable sources and transport transition ambitions include a goal for 30% EVs in new sales by 2030. Bangladesh targets a 40% clean power share by around 2040. Achieving these goals will require substantial policy adjustments.
- Climate goals and secure energy provisions will depend on technological assistance and considerable international financial flows; a net-zero pathway will require electricity decarbonization at higher speeds through renewables and with coal phase-down and to support widespread electrification of end-use sectors.

Energy transition: at a crossroads between fossil fuels and renewable energy

With 1.8 billion people in 2023, rising to 2.3 billion by 2050, the Indian Subcontinent is the most populous of our 10 world regions. The region is dominated by India, though it also includes the populous countries of Pakistan and Bangladesh. With the region's fast-growing economies and a GDP per capita rising from USD 8,500 to over USD 21,000 in 2050, the Indian Subcontinent is poised to have the ability to invest in renewable infrastructure, and for growing numbers of people to purchase many of the modern conveniences available in high-income regions – especially space cooling technology as climate change pushes temperatures ever higher.

These growing economies will see a doubling of final energy demand in our forecast period at a time when the region is at a crossroads between fossil fuels and renewable energy. Coal and its established infrastructure is still cheap, with many vested interests and employment tied to the sector. Coal traditionally powered the region and is still seen as a solution to meeting peak demand during extreme weather events. However, the region's geography and climate are favourable for renewables, which are becoming increasingly cheaper, will soon be competitive with coal, and already receive support from national governments. In the meantime, the region is energy hungry and is adding both thermal power and renewables.

India has developed the KG-D6 Satellite Cluster conventional gas field over the past several years which will help to meet some of the region's domestic natural gas needs. It still relies heavily on imported oil and natural gas, however, and will continue to do so in the future, leaving it vulnerable to supply issues and price shocks. This poses a threat to domestic energy independence and security, as we saw with the onset of the war in Ukraine. These vulnerabilities have induced some countries to go back to a dependence on coal, while others look to renewables to ensure future domestic energy security and to create an energy system where the Indian Subcontinent could conceivably export excess renewable energy in the form of green molecules.

Climate change vulnerabilities

The energy transition is especially important to this region, since it will feel the effects of climate change most acutely in the form of extreme weather events. Floods, heatwaves, and droughts are increasing in frequency and intensity, devastating both domestic and export crops, and having the greatest impact on those who are already impoverished.

These extreme weather events also challenge the uptake of renewables, as erratic weather patterns make forecasting and scheduling more difficult. In 2022, Pakistan experienced its worst floods in history, with more than one third of the country underwater at one point, wiping out buildings and crops. In the summer of 2024, India was once again hit by a heat wave that caused temperatures in New Delhi to hit 50°C, followed by heavy rainfall and floods. Extreme weather events such as these are becoming a regular occurrence. As an example, tea production in India is down 30% compared to last year, due to these two extreme weather events, with flooding in the state of Assam hindering the harvesting of tea leaves for export and driving up prices (Jadhav, 2024).

The Indian Subcontinent is at the forefront of discussions around whether counties responsible for cumulative emissions should have complete responsibility for reductions, as well as aiding the countries who are victims of this with technology, funding them to change, and even paying for the damages caused by climate change. At the same time, countries in this region realize that this transition is not going fast enough and that they need to take domestic action through energy and climate pledges. India, the largest country in the region, aims to reduce emissions intensity to 45% below 2005 levels by 2030, achieving carbon neutrality by 2070, and will continue to support greener manufacturing processes and EV manufacturing (UNDP Climate Promise, 2023b). Pakistan aims to shift to 60% renewable energy, and 30% EVs by 2030 (UNDP Climate Promise, 2023c), while Bangladesh

has revised their unconditional emissions reduction target to be 27.56 $MtCO_2e$ less by 2030 compared with business as usual (UNDP Climate Promise, 2023a). Sri Lanka aims for 70% renewable energy in electricity generation by 2030 (UNDP Climate Promise, 2023d). Nepal has several goals to increase electrification of transport and cooking (Climate Action Tracker, 2020), while Bhutan aims to have 70% of its passenger vehicle sales be EVs by 2035, a positive move when both countries already produce over 99% of their electricity from hydropower (Climate Action Tracker, 2023). The countries' abilities to follow through on these pledges will be key to increasing the use of renewable energy in the region.

Strong growth in energy need

As one of the fastest growing regions, the Indian Subcontinent's final energy demand is expected to almost double in 2050, from 40 EJ a year to 76 EJ/year (Figure 8.8.1). Manufacturing will take a greater share of the demand by sector, increasing its 38% of the mix in 2023 to 42%, and doubling in absolute terms by 2050. Transport energy demand will also double, and buildings energy demand will grow by around 40%, driven notably by an increase in space cooling.

In terms of energy carriers, we see electricity almost quadrupling to make up 34% of the final energy demand mix in 2050, at 26 EJ. The mix however is still dominated by fossil fuels – with direct use of oil, coal, and natural gas making up just under half of the final energy mix – and biomass responsible for the remaining 15%.

Electricity and renewables make some inroads

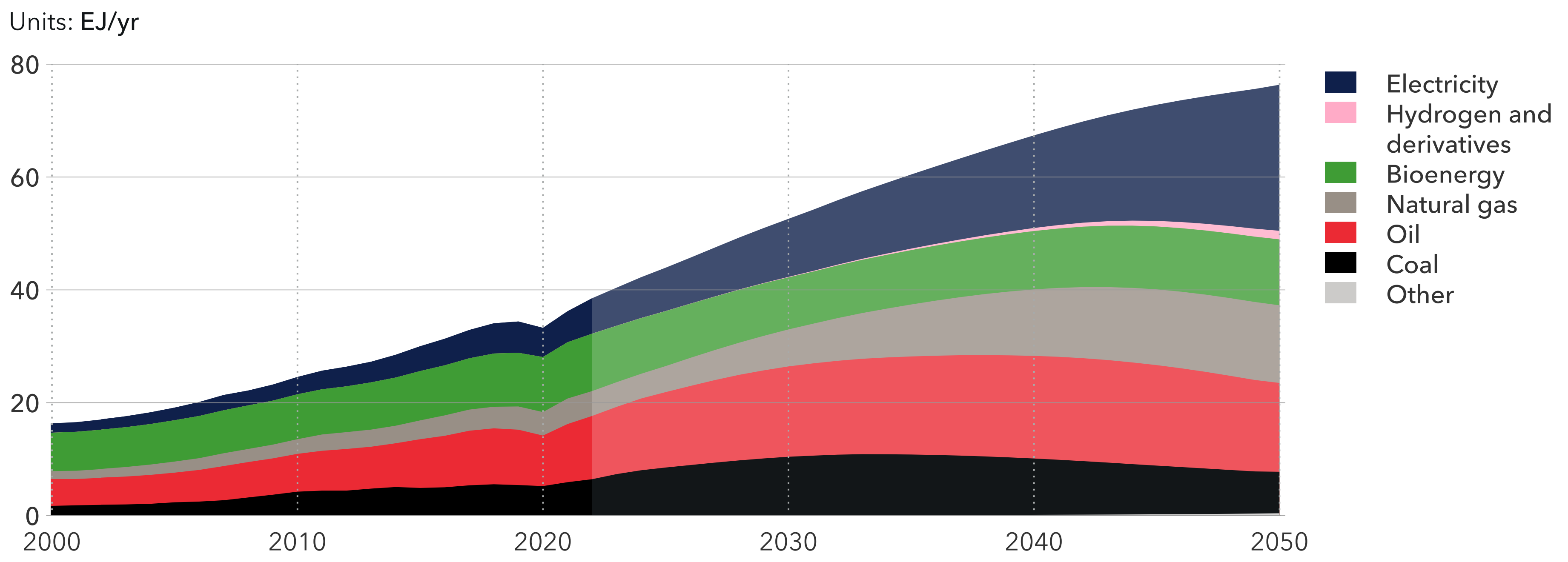
There is strong growth of electricity in buildings and manufacturing, but this is starting from a low base (Figure 8.8.2).

Although EVs exist on the market, charging infrastructure for road transport is a challenge in the region, with the exception of electric 2- and 3-wheelers where batteries can typically be charged at normal sockets domestically or by swapping batteries. We expect 75% of all sales of these smaller vehicles to be electric by the end of this decade. As the region becomes richer and more people can afford cars, the number of passenger vehicles will grow by a factor of five through to 2050. Charging infrastructure will be built out over the coming decade, and we expect the EV sales share to reach 10% in 2030 and 50% in 2040. By mid-century, we expect about 150 million EVs and still 100 million ICE vehicles on the roads in the region (Figure 8.8.3). At that time, heavy vehicles will still be dominated by combustion engines, with about 15% being electric.

In transport overall, including aviation and maritime, we see a limited uptake of electricity, to 19% of transport energy demand in 2050, with oil still being

FIGURE 8.8.1

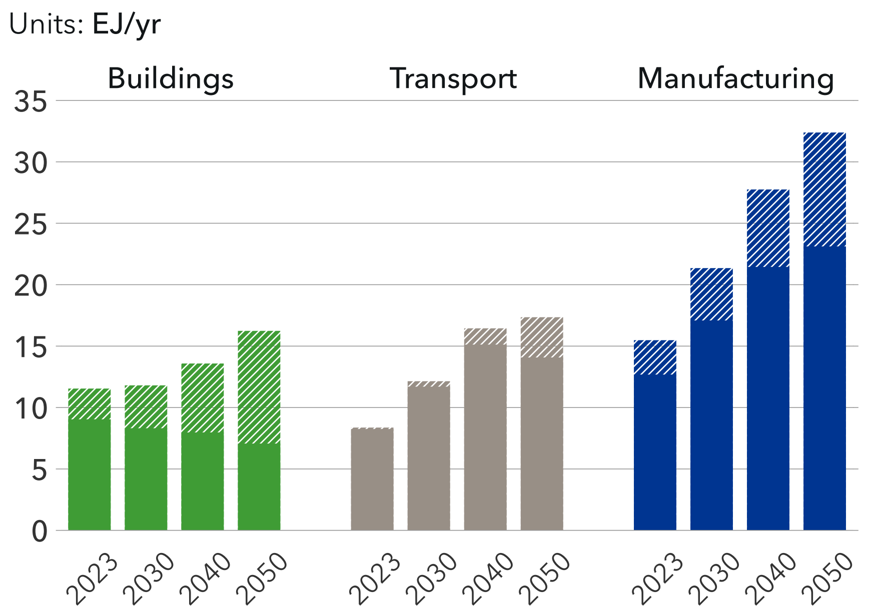
Indian Subcontinent final energy demand by energy carrier



Historical data source: IEA WEB (2024)

FIGURE 8.8.2

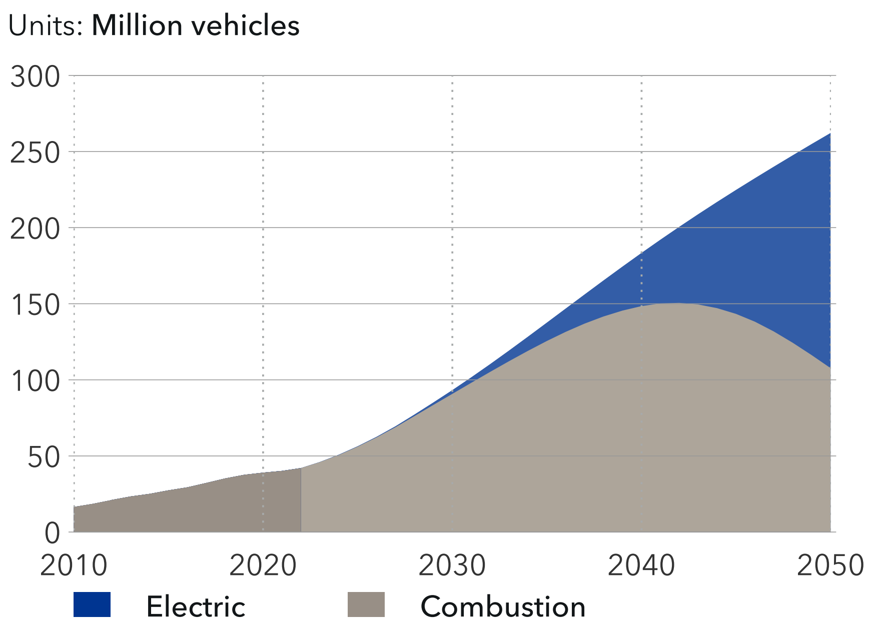
Indian Subcontinent final energy demand in selected sectors



Note: Hatching shows share of electricity in each sector.
Historical data source: IEA WEB (2024)

FIGURE 8.8.3

Indian Subcontinent passenger vehicle fleet



Note: Combustion vehicles include ICEs and PHEVs.
Electric is >99% battery electric and <1% fuel cell electric.
Historical data source: Marklines (2022), IEA EV Outlook (2023), EV Volumes (2022)

responsible for 65% of this sector's energy demand. We expect oil use to peak in 2042 and decrease slightly towards 2050.

The Indian Subcontinent is being advertised as an alternative manufacturing hub to its neighbour, manufacturing powerhouse China, for companies that want to diversify their supply chains. Growing the manufacturing sector in India is a priority of the current government, which supports this via subsidies, new labour regulations, incentives for the manufacturing of renewables components – such as batteries, PV modules, and electrolysers – and reduced import taxes on key inputs for locally made goods (Dugal and Ahmed, 2024). The growth will come primarily within manufactured goods, where India will establish a hefty production of medium-tech products, both for a fast-growing domestic market and for export. The iron and steel industry is currently experiencing rapid growth, but this will level off in the 2030s. Overall energy use for manufacturing will more than double to 2050. The manufacturing sector will also increase its electricity demand, from 18% of the mix today to 29% in 2050. This will take up the largest share, though biomass and coal follow close behind at 27% and 22% respectively.

It is in the Indian Subcontinent's buildings sector that the transition to electricity is most clear. Electricity will grow to make up 57% of building's energy demand in 2050, cutting significantly into the share of biomass, which drops from 56% to 13% in 2050. There are two drivers of this. The first is the electrification of cooking. Traditional biomass stoves – burning fuels such as animal waste, charcoal, and wood – are responsible for over 60% of cooking energy demand in 2023. By 2050 this will have dropped to 15%, with electricity rising from 9% today to 28% in 2050 – though natural gas will still be the main energy carrier for cooking at 56%. This will also temper the growth in energy demand for the buildings sector, as both electric cooking and gas cooking are much more energy efficient than biomass cooking. The second, and most important, is the growth in the demand for space cooling, which is 100% electric. With rising GDP per capita leading to more people having access to space cooling technology, and climate change causing more adverse heat events, demand for space cooling will increase from just 3% of the mix today to over 21% in 2050 – a ninefold growth in absolute terms.

The region is currently using 6 Mt of hydrogen for feedstock and direct reduction, all of it from fossil fuel. India already has ambitions to produce significant amounts of green hydrogen in 2030, but given the present challenges regarding sufficient renewable electricity, it is far from certain that these ambitions will be met. DNV's long-term forecast is that in 2050 the region will use about 16 million tonnes of hydrogen, with a mix of green, blue, and grey hydrogen. In total, this constitutes about 0.7% of the region's final energy use. Shares will come from ammonia and e-fuels used in maritime and aviation sectors.

Peak fossil fuels a significant step in the right direction

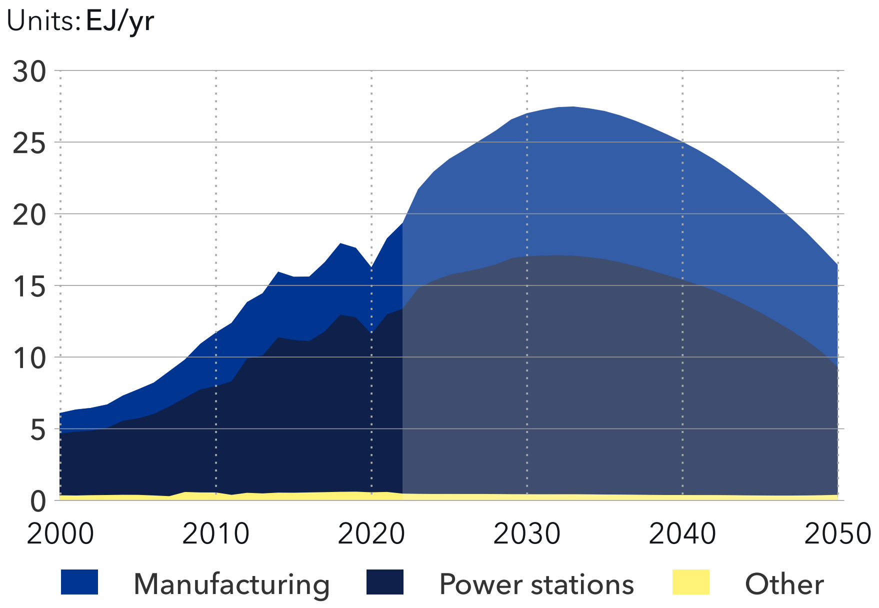
Coal peaks in 2033 and oil in 2041, while gas does not peak before 2050, (Figure 8.8.7).

Coal is mainly used in power generation (66%) and in manufacturing (32%) (Figure 8.8.4). In both these sectors, coal use will peak in the early 2030s. Cheap solar and wind will outcompete coal in the power sector, and an increasing share of electricity will enter the manufactured goods sector.

Oil is mainly used in transport (63%), followed by feedstock (14%), and manufacturing (12%). Overall oil use will grow 50%, due to significant increases in road transport and aviation, before it peaks in 2042 and starts to decline due to increased electrification of road transport.

FIGURE 8.8.4

Indian Subcontinent coal demand by sector



Historical data source: IEA WEB (2024)

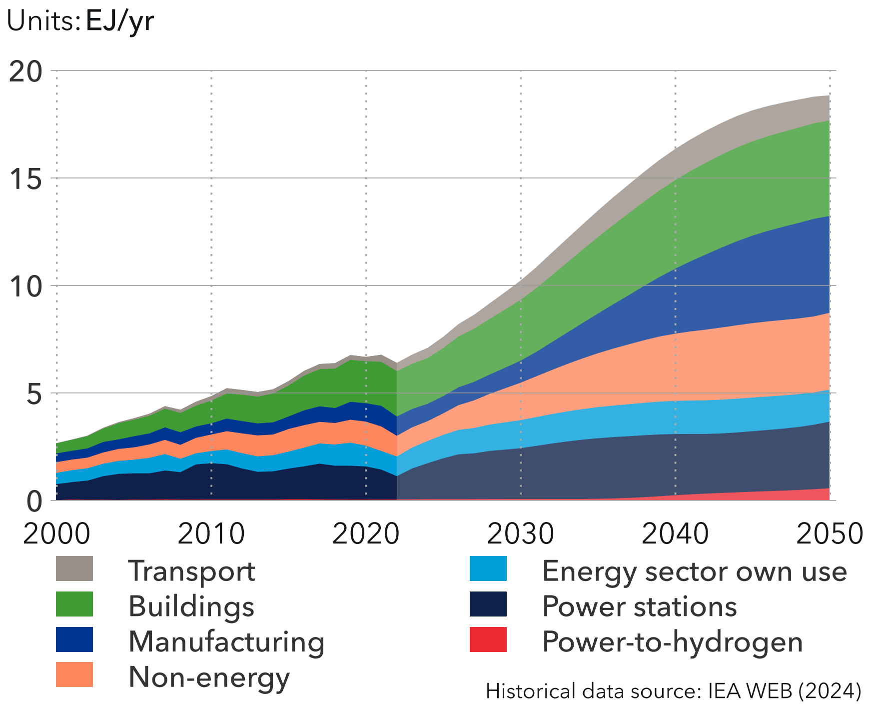
Natural gas use will nearly triple to 2050. As shown in figure 8.8.5, Natural gas use will increase significantly in all the major sectors where it is used (Figure 8.8.5). By mid-century, it approaches an even distribution with about 20% each in manufacturing, buildings, power generation, and feedstock.

Imports of oil and gas threaten energy security

Of our 10 world regions, the Indian Subcontinent will be second only to Greater China in terms of coal production and consumption. Through the 2030s, the region will not meet all its coal requirements domestically and will need to import coal from other regions. This is partly related to coal quality and partly to coal availability. Coal production in the Indian Subcontinent will come closer

FIGURE 8.8.5

Indian Subcontinent natural gas demand by sector



Historical data source: IEA WEB (2024)

to its level of consumption from 2040 onwards, as peak energy demand for this carrier will have passed.

Oil and gas are a different story. The region is utterly dependent on import of these commodities from other countries, notably those in the Middle East. Lately, the region has also significantly increased its import of rebated Russian oil. We see this in Figure 8.8.6, which shows that the Indian Subcontinent will be importing close to 100% of the oil it needs in 2050. India's KG-D6 Satellite Cluster will boost domestic gas production, but at just over 50% in 2050 imports are still high, indicative of a dependence on imports. With insufficient domestic resources, there will always be a sizable gap between how much oil and gas the region consumes and how much it produces. This is costly, makes the region vulnerable from an energy security perspective, and hinders the Indian Subcontinent's energy independence.

Rise of solar and wind

There is exciting potential for solar and wind power and we see these renewables make impressive inroads in primary energy supply and the electricity power mix. Although this happens later than in higher income regions, it is important nonetheless.

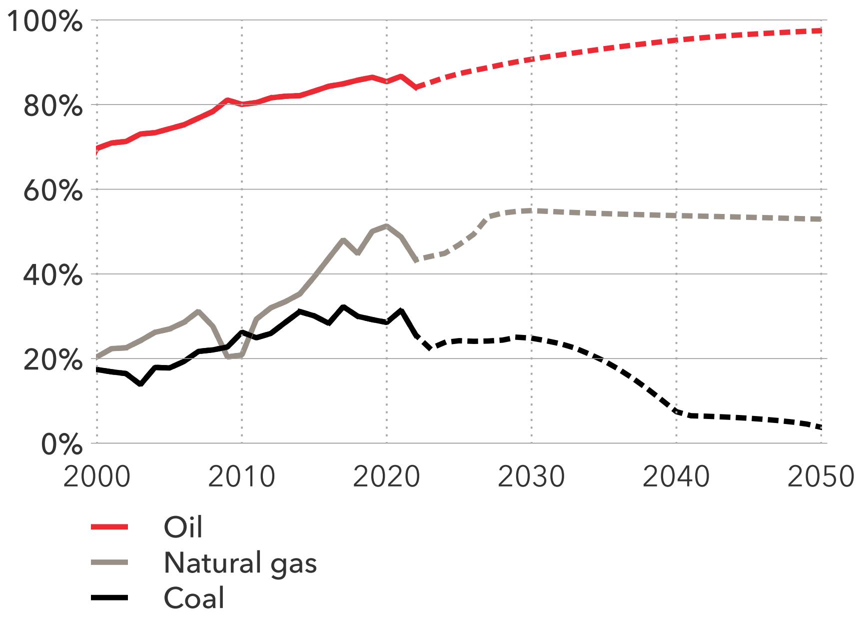
In the primary energy supply, we see the rise of solar and wind power in the 2040s, so that by 2050 solar makes up 18% of the mix, and wind 6% (Figure 8.8.7). The Indian Subcontinent will be responsible for 15% of the world's solar primary energy supply, nearly tied with North America for second place behind Greater China. Given that North America is starting from a much higher solar PV capacity today, this growth in the Indian Subcontinent is significant. Wind power in the Indian Subcontinent in 2050 will be around 6,000 PJ/yr, in the same range as Latin America and the Middle East and North Africa. These two sources make up for a good portion of the growth in primary energy supply from the mid-2030s onwards, with coal and oil peaking in 2033 and 2042 respectively, though natural gas continues to grow slightly. Fossil fuels will, however, still make up over 50% of the primary energy mix in 2050. We see a small role for nuclear power in the region, making up just 3% of the primary energy supply mix in 2050.

Renewables will make the most inroads in electricity generation, where we will see coal use decline from 2032 onwards (Figure 8.8.8). In 2050, over 70% of electricity generation in the Indian Subcontinent will be from renewables – predominantly solar, but also wind and hydro. Of all our regions, the Indian Subcontinent will have the second highest proportion of solar PV in the electricity mix, behind Greater China, and a growing share of the solar PV will be installed as solar PV with storage. The region is geographically suited for installations of wind

FIGURE 8.8.6

Indian Subcontinent share of fossil fuel consumption not produced domestically

Units: Percentages

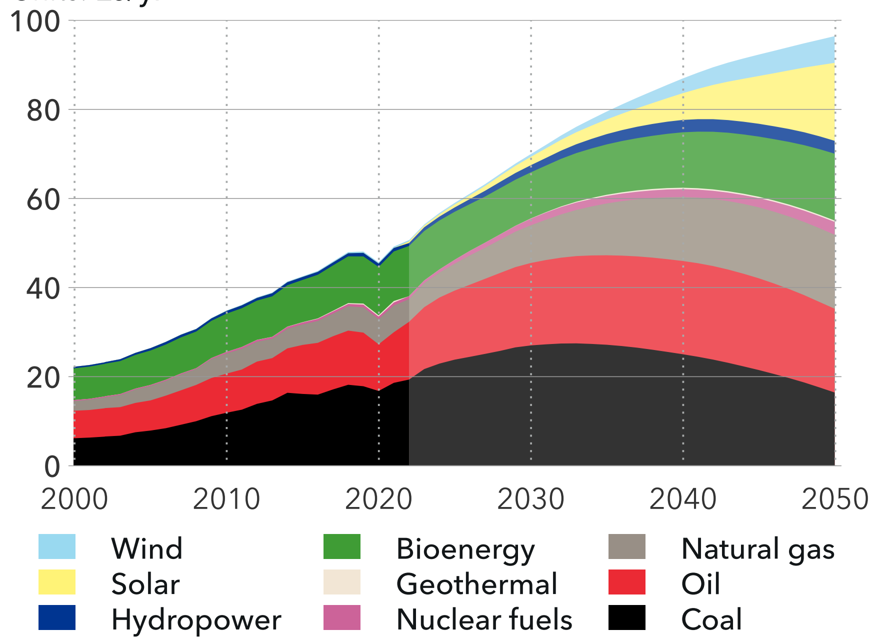


Historical data source: IEA WEB (2024)

FIGURE 8.8.7

Indian Subcontinent primary energy consumption by source

Units: EJ/yr

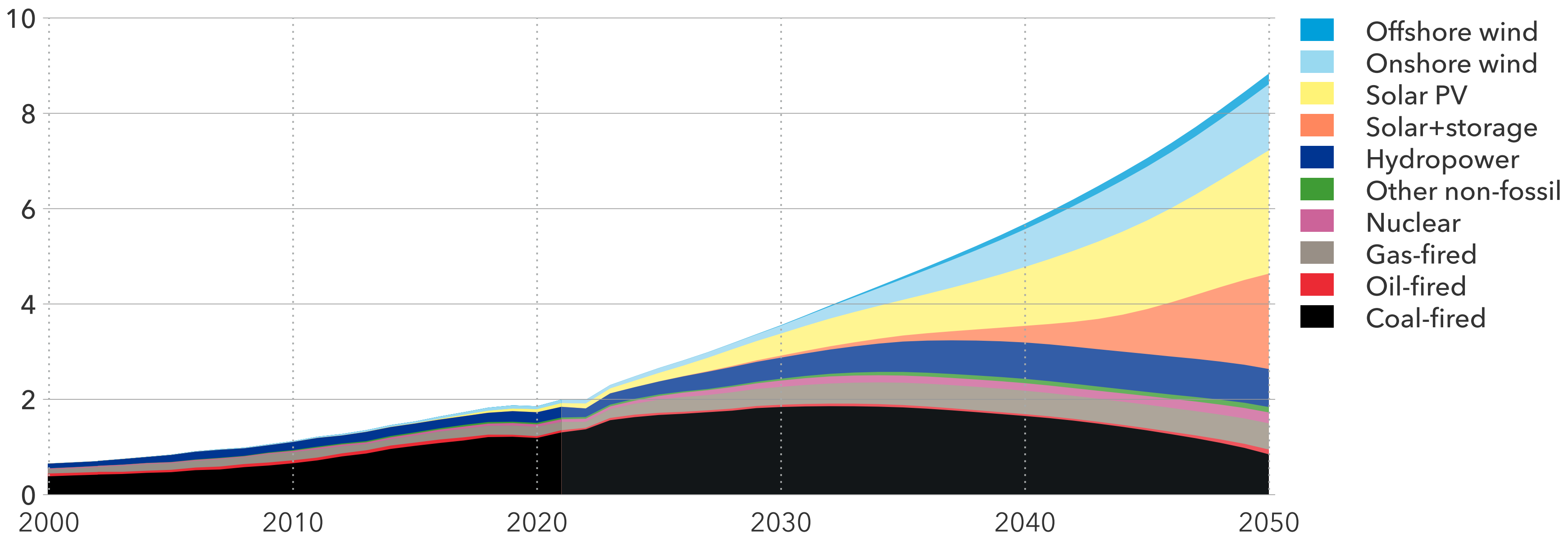


Historical data source: IEA WEB (2024)

FIGURE 8.8.8

Indian Subcontinent electricity generation by power station type

Units: PWh/yr



Historical data source: Global Data (2024), IRENA (2024), IEA WEB (2024) and solar; in today's India, solar installations are more commonly found in the west of the country, though there is potential for installations across the country. In onshore wind power, the states of Gujarat and Tamil Nadu currently have the most capacity along with the best potential for offshore wind – the Indian government has allocated around USD 1bn for Gujarat and Tamil Nadu to each develop of 500 MW of offshore wind (Jenkinson, 2024). Renewables will be responsible for meeting the needs of electricity demand growth, even more so than its role in meeting primary energy growth. While we do not see the complete phase-out of fossil additions to the grid by 2050, they will be dwarfed in comparison to the capacity of renewables added.

Peak emissions before 2040

The Indian subcontinent today uses 54 EJ of energy, just below 9% of global energy use. With a significant growth in both population and economy, and with the region industrializing at the same time, the region's overall primary energy will almost double to 2050, by which time the region will be using 15% of the world's energy. Historically, energy use per capita in this region has been low, but we can see it growing from 28 GJ/person today to 41 GJ/person in 2050, an increase of 46% (Figure 8.8.9). Though the share of non-fossil energy use will increase, energy use per capita will still be 53% fossil in 2050.

Today, the Indian Subcontinent's energy related emissions are a little over 3 GtCO$_2$, around the same level as the Middle East and North Africa and Europe.

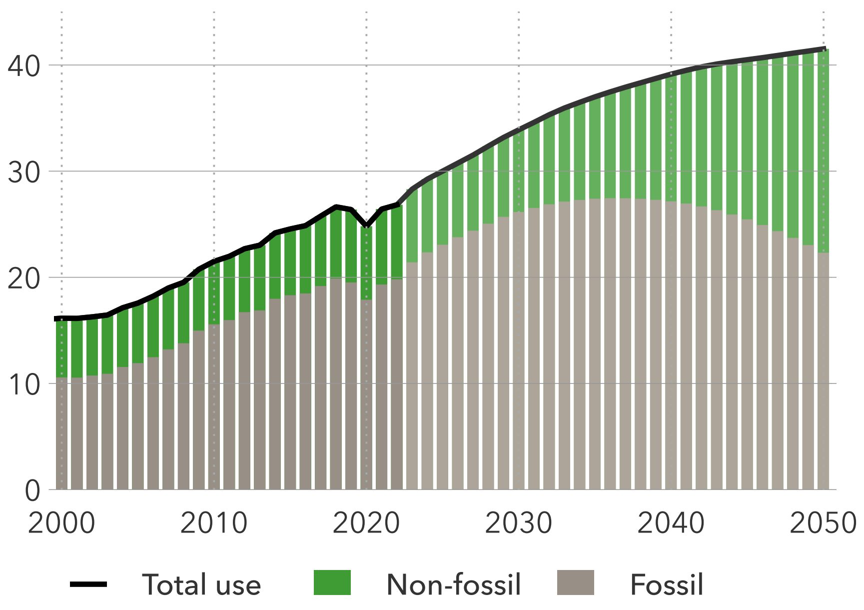
When fossil fuel use peaks, emissions will also peak. As shown in figure 8.8.10, we find that the Indian Subcontinent's energy-related CO$_2$ emissions will peak in 2037 and then decline to reach 3.2 GtCO$_2$ in 2050. In addition, we have process emissions not shown in the figure at about 0.65 Gt in 2050.

The region's share of global energy-related CO$_2$ emissions will double from 9% today to 18% in 2050. In terms of energy carriers, emissions will be split 43% coal, 33% oil, and 24% natural gas. On a sectoral level, power (32%), manufacturing (28%), and transport (28%) have an even share, with buildings much smaller at 8%.

FIGURE 8.8.9

Indian Subcontinent energy use per capita

Units: GJ/(person-yr)



Historical data source: IEA WEB (2024)

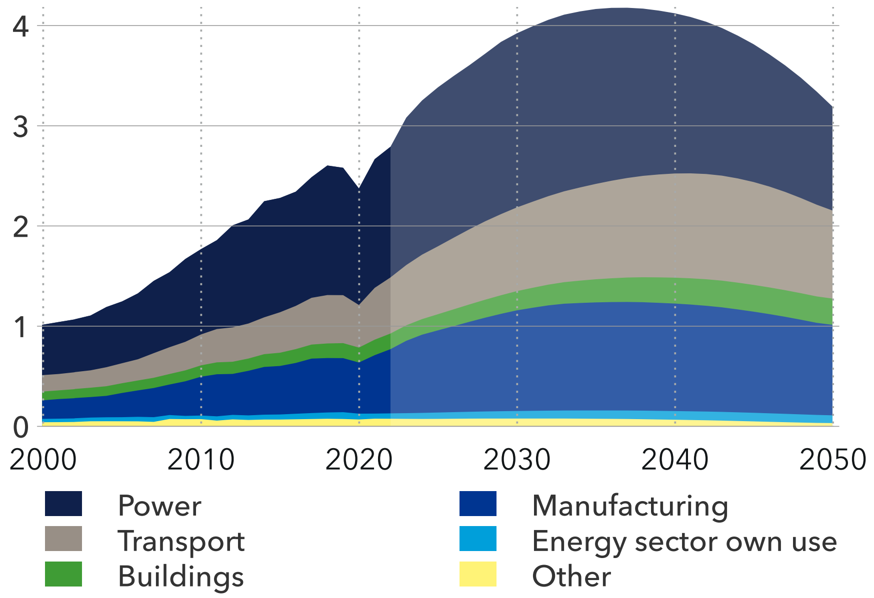
The region's per capita energy-related CO$_2$ emissions are today at 1.6 t/person, which is 38% of the global average. Despite economic growth, the per capita emissions will fall to 1.3 t/person in 2050, to be 74% of the global average.

India is the world's most populous country, and this region has the highest population out of our ten regions. The region also has strong economic growth; what happens with emissions in this region is crucial for the global emissions trend. As such, it is encouraging that, according to our findings, the region's emissions will peak before 2040 and be back to present levels by 2050. The main reason for this is that renewable electricity is increasingly competitive with coal, and that electricity is entering new sectors of demand. Our ETO forecast ends in 2050, and between 2023 and 2050, the region increases energy-related CO$_2$ emissions less than 4%. The emissions peak reached in 2037 is followed by a decreasing trend, which is promising for net-zero emission trajectories not too long after mid-century, for example India's goal to be carbon-neutral by 2070.

FIGURE 8.8.10

Indian Subcontinent energy-related CO$_2$ emissions by sector

Units: GtCO$_2$/yr



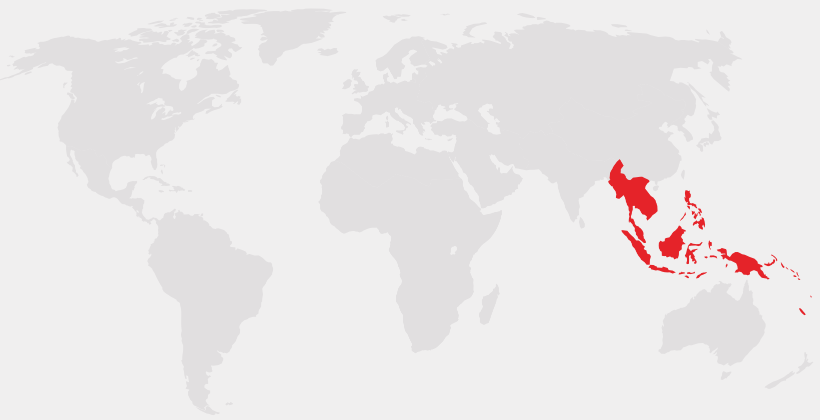
Historical data source: IEA WEB (2024)

In the context of global climate policy, the Indian Subcontinent's country NDC pledges aim to limit growth in emissions to no more than 320% by 2030, relative to 1990. Our Outlook indicates energy-related CO$_2$ emissions increasing by 547% over this period. There are uncertainties in comparing our forecast with pledges, as some major countries also include non-energy-related CO$_2$ emissions in their targets. India is committed to reducing carbon intensity of GDP by 45% between 2005 and 2030, similar to how China sets its reduction target. Our forecast (considering energy and industrial process-related CO$_2$ emissions) suggests a reduction of 36% in carbon intensity by 2030 for the region.

> We find that the Indian Subcontinent's energy-related CO$_2$ emissions will peak in 2037 and then decline to reach 3.2 GtCO$_2$ in 2050.

8.9 SOUTH EAST ASIA (SEA)

This region stretches from Myanmar to Papua New Guinea and includes the Pacific Island States.



Thailand, Indonesia, Malaysia, and Vietnam account for **80%** of region energy use.

	Population (Million)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/person (tonnes)
2023	696	11.1 15 900	34 48	1.9 2.7
2050	798	26.2 32 900	48 60	1.6 2.0

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.9 SOUTH EAST ASIA (SEA)

Current position

South East Asia has diversified resources including solar, wind, hydropower, and geothermal potential. The region also has significant reserves in several key critical minerals (Phoumin, 2024).

The region is a net importer of oil and approaching an import situation in coal – although Indonesia is one of the world's largest producers and exporters – and LNG import capabilities are bolstered as part of 'transitional fuel' strategies.

Regional cooperation is longstanding through the Association of Southeast Asian Nations (ASEAN), comprising 10 region countries which work on alignment in energy ambitions to some extent.

Economic relations with China have been fortified in BRI development and infrastructure projects (Busbarat et al., 2023). The Asia Zero Emission Community (AZEC) initiated by Japan (2023) advances decarbonization. The G7 Partnership for Global Infrastructure and Investment supports the JETPs with Indonesia and Vietnam to accelerate retirement of coal-fired power plants. The EU-ASEAN partnership (Global Gateway) committed USD 11bn (EUR 10bn) to sustainable connectivity and infrastructure investments.

ASEAN represents the world's fourth largest energy consumer. Economies and populations are growing. Emissions are rising, and the power sector is the region's largest sectoral contributor to CO_2 emissions. However, several countries in the region have net-zero targets: Cambodia, Lao PDR, Malaysia, Papua New Guinea, Vietnam, and some of the Pacific Island states in 2050; Indonesia in 2060; and Thailand in 2065.

Climate change is a pressing concern in South East Asia. Myanmar, the Philippines, and Thailand all rank in the top ten most at-risk countries globally (Eckstein et al., 2021) with risks ranging from typhoons and floods to long, heavily populated, low-lying coastlines vulnerable to rising sea levels.

Pointers to the future

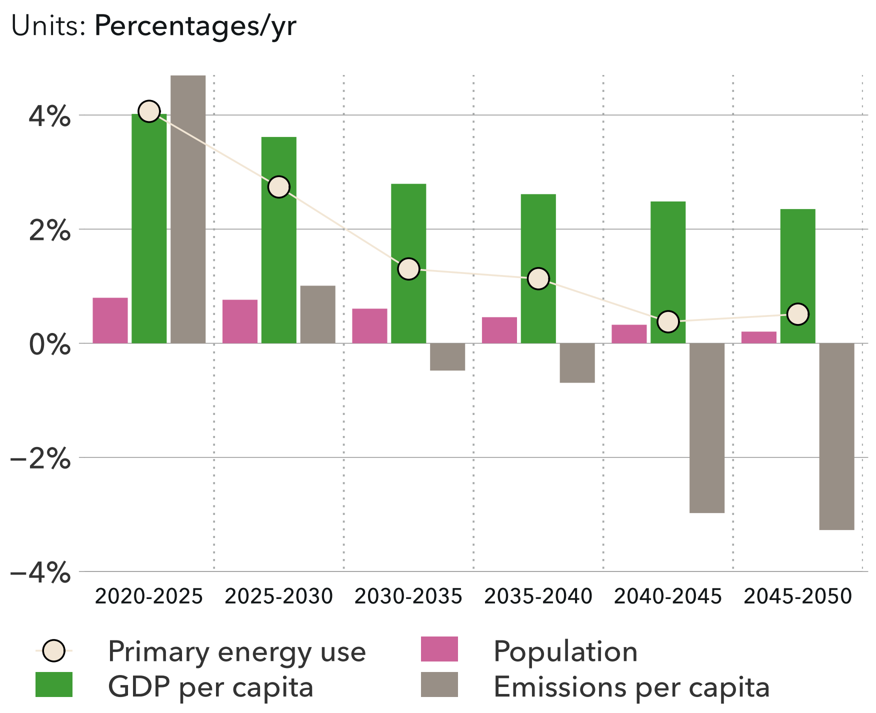
- South East Asia's rising energy demand means fossil-energy buildout continues.
- The next cycle of *ASEAN Plan of Action for Energy Cooperation* (APAEC) post 2025 is under development and will continue bolstering renewable electricity beyond the existing collective aim to raise the share of renewable energy to 23% of primary energy supply and a 35% share in the power mix by 2025.
- With targets favouring renewable power penetration – national support through competitive tendering (Malaysia, Vietnam) while the region trend is feed-in tariffs, PPAs with state electricity companies (e.g. in Thailand) – flexibility sources (battery energy storage, pumped hydro) will increasingly be included in policy frameworks (Thailand and Vietnam).
- Enhancing energy interconnectivity becomes increasingly crucial in the context of advancing the transition (DNV, 2024). A step towards an interconnected future was taken with the launch of the *ASEAN Power Grid Advancement Programme*, 2023. However, main barriers such as coordination across diverse regulatory frameworks, policies, and market structures must be overcome.
- Interest in green and low-carbon hydrogen is emerging. Overall, there are negligible hydrogen incentives, except for Singapore which will support hydrogen imports to eventually supply 50% of power needs by 2050 (Villegas, 2024).
- Multiple taxonomies, such as *ASEAN Taxonomy* and related national releases, classify economic activities that are compatible with climate goals, and these will impact development of incentive/disincentive policies, including facilitation of an orderly phaseout of coal-fired power.
- There is growing focus on CCS projects in the region, yet low carbon prices will discourage uptake in power and end-use sectors.

Growing in all directions – energy demand, industry, population, and income

South East Asia is a diverse region experiencing a period of growth in many areas, including population, economic activity, GDP, participation in global energy supply chains, and energy demand. Its young population with increasing purchasing power, rich resources, and advantageous geographic position on major international trading routes all point to a prolonged period of growth. The key indicators in Figure 8.9.1 show economic activity in the region anticipated to surge, with trade among Association of Southeast Asian Nations (ASEAN) expected to grow by USD 1.2trn in the coming decade.

FIGURE 8.9.1

South East Asia key indicators of growth



The region appears well positioned to shift towards renewable energy given its vast renewable potential, especially in solar and wind. However, an entrenched dependence on fossil fuels could hamper this transition. An abundance of coal and natural gas resources propels South East Asia's continued reliance on fossil fuel for both power generation and primary energy supply. Globally, the region is a top exporter of coal, primarily from Indonesia and, to a smaller extent, Vietnam.

Despite the enormous potential for South East Asia to achieve an energy transition, major obstacles remain. These include lack of access to finance and technology, regulatory misalignment across the region, limited local expertise and knowledge, and infrastructural systems locked-in to fossil fuel energy (ETP, 2023). These key areas will require concerted effort and focus to achieve an energy transition in the region.

Fossil-fuel dependency is difficult to shake

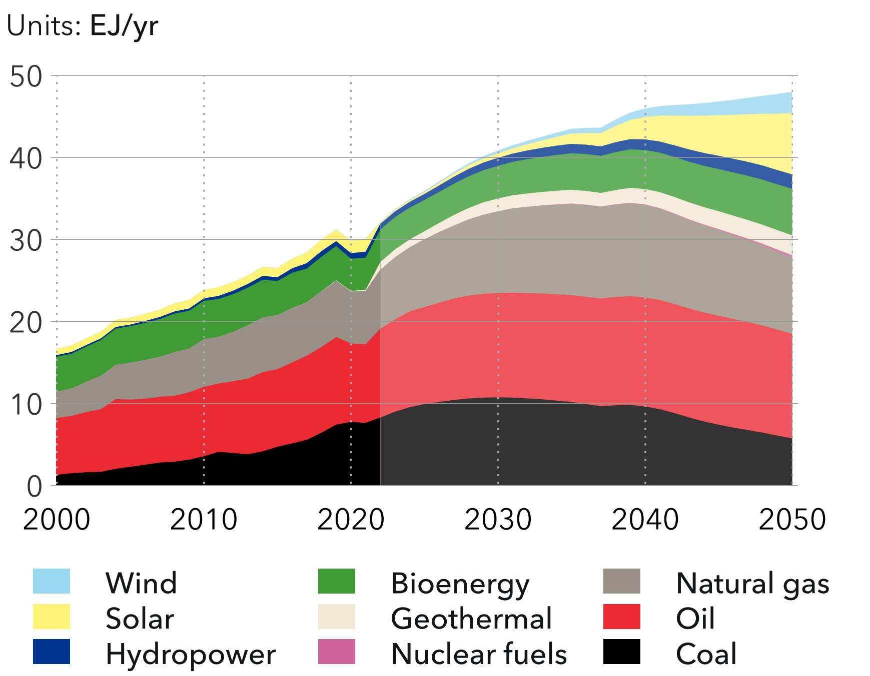
Dependence on fossil fuels is a major roadblock in the energy transition in South East Asia. This is apparent in the region's pattern of primary energy consumption. Figure 8.9.2 shows that over 80% of primary energy consumption originates from fossil fuels today. This proportion is expected to decrease to around 58% in 2050, which is higher than all other low- and middle-income regions, except for the oil-and-gas-dominant regions of the Middle East and North Africa and North East Eurasia.

There are plans to decrease reliance on fossil fuels across the region. Indonesia, Vietnam, the Philippines, Singapore, and Brunei all aim to phase out coal power in the 2040s with a range of strategies. In Singapore for example, hydrogen and hydrogen-derived fuels are seen as key technologies for reducing reliance on fossil fuels, especially in the maritime sector as Singapore is home to one of the world's busiest ports. However, policies to support fossil-fuel phase outs are fragmented and lack comprehensive coverage and political will. Indonesia and Vietnam, the region's two largest coal producers, have not yet retired any coal power plants this century (Do and Burke, 2024).

Fossil fuels play a key role in South East Asia's energy production and economic activity. This represents the key ongoing challenge facing the region: balancing economic growth, energy security, and climate objectives. Energy security has long been cited as an advantage that promotes continued use of fossil-fuels in the energy system. However, surging coal prices in 2022 caused a jump in production costs in Vietnam, the Philippines, and Cambodia, resulting in higher electricity prices and losses for national utilities (Doleman, 2024). Exposure to volatility in fossil-fuel prices leaves the region vulnerable to increased risk and undermines energy security. Diversification of the energy mix can shield the region from some of these market-based risks, and significantly advance its economic stability and environmental sustainability.

FIGURE 8.9.2

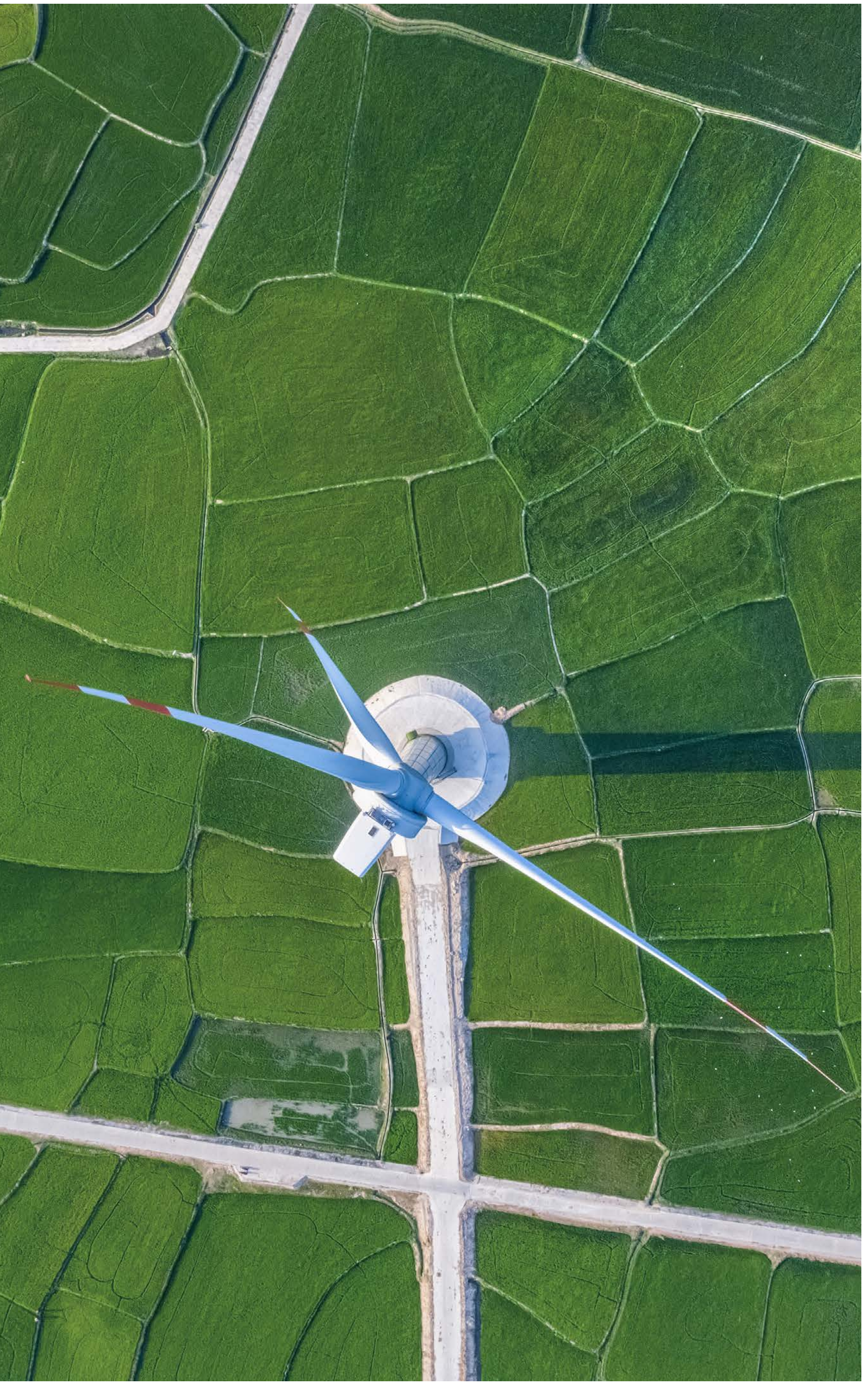
South East Asia primary energy consumption by source



Historical data source: IEA WEB (2024)

> The key ongoing challenge facing the region: balancing economic growth, energy security, and climate objectives.

The region's coal plants are some of the youngest in the world, with an average age under 15 years. Phasing out its coal plants early could lead to additional costs exceeding USD 270bn (Do, 2024b). Early phase out of coal would be particularly impactful in Indonesia, which is one of the world's biggest coal producers. Phasing out fossil fuel requires targeted policies, such as carbon-pricing mechanisms in Indonesia. Additionally, policy initiatives to support vulnerable fossil-reliant workers and communities should be considered to achieve equitable energy transition outcomes across the region.



Vast yet unrealized renewable potential

South East Asia has immense potential for renewable energy production, particularly through solar and wind, and to a lesser extent geothermal and hydropower. There appears to be commitment to increase renewable energy production in ASEAN's *Plan of Action for Energy Cooperation* (APAEC) to 2025 aiming to achieve 23% renewable energy in its energy mix and pursue energy efficiency measures. Several of the major economies like Indonesia, Malaysia, Thailand, the Philippines, and Vietnam also have national installed-capacity targets for renewables from 2030 to 2050. As things stand, however, this potential remains untapped.

There are over 220 GW of utility-scale solar and wind energy projects in the prospective phase of development in ASEAN alone, however only around 3% of these are currently under construction (GEM, 2024). This unrealized potential is characteristic of slow renewable energy uptake in a region plagued with issues like carbon lock-in, insufficient finance, and a lack of local technical expertise.

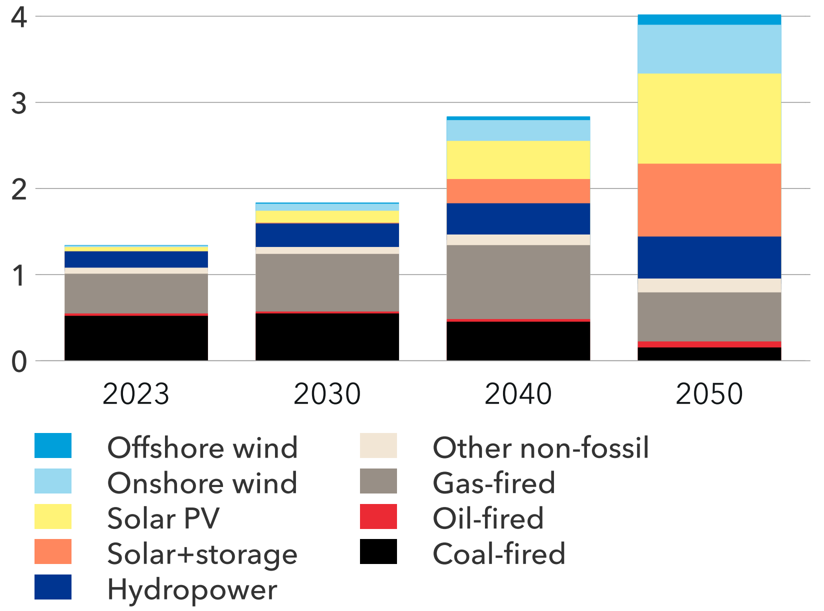
Vietnam, as the pioneer of renewable energy uptake in the region, is a notable exception. Vietnam is taking steps towards renewable electrification through the implementation of the *Power Development Plan 8* (PDP8) to 2030. It outlines plans to ramp up renewable energy, as well as investment in grids to foster regional energy cooperation with neighbouring countries (Cyrill, 2024). PDP8 complements existing feed-in tariffs to support renewable energy uptake. This ambitious policy has propelled Vietnam to the top of renewable energy production in South East Asia, accountable for over 19 GW of capacity – more than double the combined total of the next three leading countries: Thailand (3.1 GW), the Philippines (3 GW), and Malaysia (1.6 GW).

On a regional level, we expect that renewable energy will continue to grow slowly in the coming years, but growth will quicken from the 2030s. Figure 8.9.3 shows that the share of renewable energy in the electricity mix will increase from around 25% today to almost 80% in 2050, largely due to uptake of solar and solar+storage technologies. Broadly speaking, renewables are satisfying new energy demand growth in the region, yet not displacing fossil sources to any significant degree.

FIGURE 8.9.3

South East Asia grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

Cooperation is essential for the transition

South East Asia's energy transition relies on international cooperation. To meet net-zero emissions goals, renewable energy targets, and fossil-fuel phase-out plans, the region requires financial and technical assistance from the international community. International support is stipulated as a condition for achieving higher emissions reduction targets in the NDCs of Indonesia, the Philippines, Thailand, and Vietnam. The *Just Energy Transition Partnerships* (JETPs) signed in 2022 to support the equitable energy transition in Indonesia (USD 20bn) and Vietnam (USD 15.5bn) were a milestone for securing international finance in the region. Initiatives like the *Energy Transition Mechanism* also contribute funding for energy transition projects, but further financial support is needed in the region.

Existing cooperation with neighbouring countries like Australia – which cites the ASEAN bloc as its second largest trading partner after China – underlines the importance of inter-regional cooperation for the energy transition. Australia launched a USD 1.2bn fund in 2024 to support trade and investment in South East Asia, with a focus on renewable energy and infrastructure. Similar support from other neighbours like China and Japan, and global players like the EU and the US are necessary to achieve a just energy transition in the region. Perceived and real risks associated with investing in emerging markets may hinder the expansion of international investment. Innovative finance mechanisms, such as blended finance, should be pursued to reduce the risks of investing in South East Asia (Bain & Company et al., 2024).

> To meet net-zero emissions goals, renewable energy targets, and fossil-fuel phase-out plans, the region requires financial and technical assistance from the international community.

Cooperation within the region is on the agenda. The ASEAN Power Grid (APG) aims to connect the power systems of member countries with the goal of sharing renewable energy, thus reducing reliance on fossil fuels in electricity generation. Existing pilot initiatives like the *Lao PDR-Thailand-Malaysia-Singapore Power Integration Project* (LTMS-PIP) – which transfers hydropower electricity from Lao PDR to Singapore via Thailand and Malaysia – can inform larger, multilateral projects such as the APG (DNV, 2024). An in-depth analysis of the ASEAN power sector can be found in DNV's *2024 ASEAN Interconnector Study: Taking a Regional Approach to Decarbonization*. Cross-border electricity trade comes with economic and geopolitical benefits, strengthening the region's security and integration in the global energy supply chain.

As the global geopolitical landscape becomes increasingly complex, companies are looking to de-risk their supply chains by reducing reliance on single markets. South East Asia is well placed to meet this demand for security through diversification of the supply chain, especially in the manufacturing space. Its young and dynamic population, diverse economies, and a relatively neutral geopolitical stance in the global landscape makes South East Asia an attractive alternative to China (BCG, 2024). Established sectors which have potential to grow include solar PV manufacturing in Vietnam and Malaysia; EV production in Thailand and Indonesia; rare earth mineral mining in Vietnam and Myanmar; and nickel mining in Indonesia and the Philippines.

Road transport driving oil dependency

There is a huge opportunity to reduce South East Asia's transport sector oil dependency via rapid electrification of the passenger vehicle fleet. We forecast that 69% of the region's oil demand in 2050 will come from road transport, only slightly less than today's situation. Transport sector annual oil demand will grow to 8.5 EJ in the early 2030s, then plateau before declining slightly to 7.7 EJ in 2050. In this time, the region's vehicle fleet grows from about 323 million vehicles to more than 513 million.

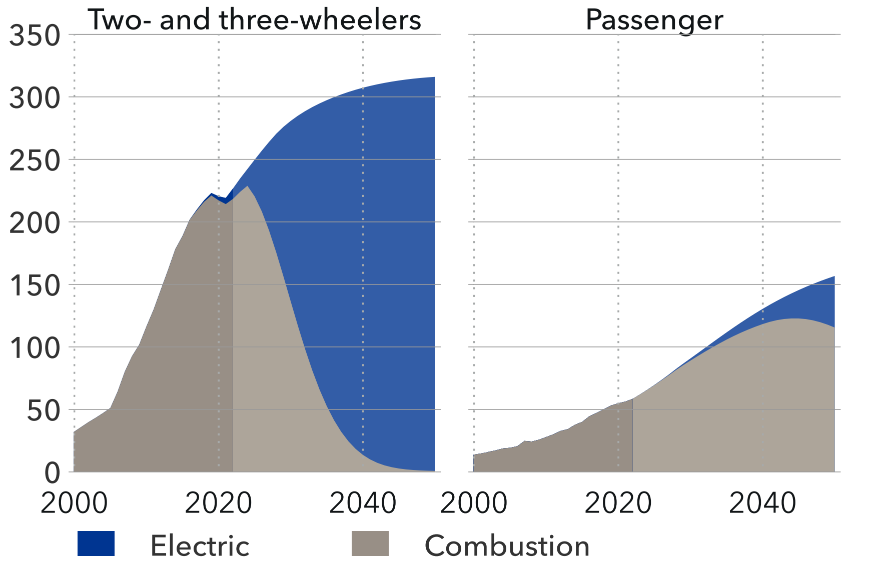
The growth of four-wheelers reflects the region's growing wealth and demand for passenger vehicles, primarily chosen for greater comfort and range over two- and three-wheelers. Consequently, we predict a two-and-a-half-time increase of the passenger vehicle fleet from 62 million in 2023 to 157 million by mid-century. We anticipate that the passenger vehicle fleet will consist of over three-quarters internal combustion engine vehicles (ICEVs) in 2050, but there will be some growth in EVs, primarily driven by demand in Thailand and to a lesser extent Indonesia and Malaysia (Do, 2024a). The commercial vehicle fleet will grow from around 26 million in 2023 to 40 million in 2050, with little electrification.

EV adoption will lag far behind regions such as Greater China. Several factors contribute to the slow uptake of EVs in South East Asia: higher initial costs compared to ICEVs; total cost of EV ownership; few supportive policies like EV adoption targets and consumer incentives at point of sale; regulatory delays and uncertainties from governments; and under-developed vehicle battery charging infrastructure, which limits accessibility and convenience for EV users. An overarching issue is a lack of renewable energy capacity to support EV demand; electricity generation is still dominated by coal and gas.

FIGURE 8.9.4

South East Asia number of road vehicles by type and drivetrain

Units: Million vehicles



Note: Combustion includes ICEs and PHEVs.
Electric is >99% battery electric and <1% fuel cell electric.
Historical data source: Marklines (2022), IEA EV Outlook (2023), EV Volumes (2022)

Countries in the region should look to the ambitious policies of Thailand, which aims to phase out new ICEV sales by 2035 and to have 50% of all local car production be EVs by 2035 (Wong, 2023). Although there are some other policies in the region to support EV uptake, like Singapore's goal to have a 100% renewable-powered fleet by 2040 and EV consumer subsidies in Indonesia, Malaysia, and Philippines, the policies remain too weak to significantly impact EV uptake in the region.

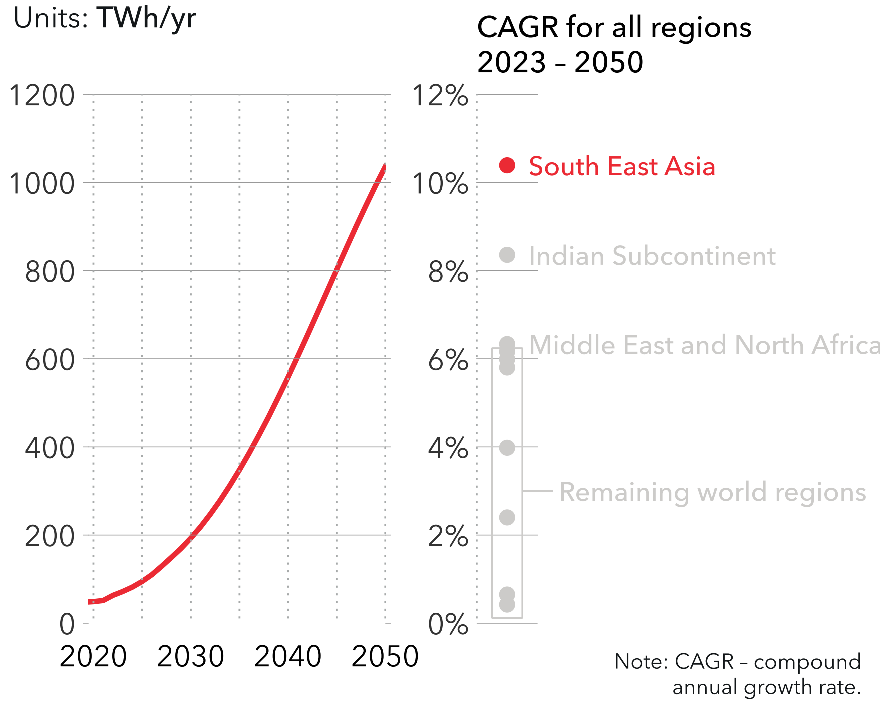
South East Asia also boasts a substantial fleet of two- and three-wheeled vehicles alongside its four-wheelers. This two- and three-wheel fleet is forecast to grow by from 235 million vehicles in 2023 to 316 million by 2050. We estimate that fewer than one million of the 316 million in mid-century will be ICEVs, implying that an impressive 99% will be electric two- or three-wheelers (Figure 8.9.4). Despite this growth, the share of two- and three- wheelers of total vehicles drops from 73% in 2023 to 62% in 2050, reflecting the income-influenced change in demand patterns for vehicles.

Impacts of climate change are evident

Climate change is a pressing concern in South East Asia. Recent examples include tropical cyclone Yagi which devastated Vietnam, Thailand, Myanmar, and Lao PDR in 2024; recording-breaking rainfall in the Philippines; and deadly heatwaves across mainland South East Asia. The intensification of tropical cyclones poses a significant threat to the security of energy systems; nearly half of installed solar PV and hydropower capacity, over 40% of wind turbines, and more than 20% of grid infrastructure in the region are situated in cyclone-prone areas (IEA, 2024). Extreme weather events damage infrastructure, impact economic activity, and strain electricity supplies. Pressure on the electricity system is especially noticeable during heatwaves when the need for cooling surges – a pattern expected to persist until 2050. Of the ten ETO regions, South East Asia has the fastest growth in demand for cooling (Figure 8.9.5). By 2050, the demand for cooling accounts for almost 30% of the total electricity demand. The rising demand for cooling is bolstered by the region's growing income, enabling more people to afford cooling solutions like air conditioning.

FIGURE 8.9.5

South East Asia cooling energy demand growth



Note: CAGR - compound annual growth rate.

Of the ten ETO regions, South East Asia has the fastest growth in demand for cooling.

The Pacific Islands are also under immense threat from climate change. Ocean warming, ocean acidification, and rising sea levels that are well above the global average are a looming danger – 90% of the population lives within five kilometres of the coast and half the infrastructure is within 500 metres (WMO, 2024). The triple-pronged threat to ecosystems, livelihoods, and economies that rely on the ocean puts the Pacific Islands in a precarious position. To highlight the urgency of sea level rise, Tuvalu's foreign minister addressed COP 26 in 2021 from a lectern knee-deep in seawater. Part of this address was a push for more immediate climate action. Many countries in South East Asia have historically contributed very few emissions compared to wealthy countries which industrialized earlier, but bear a disproportionate burden of the resulting climate changes.

Targets and emissions

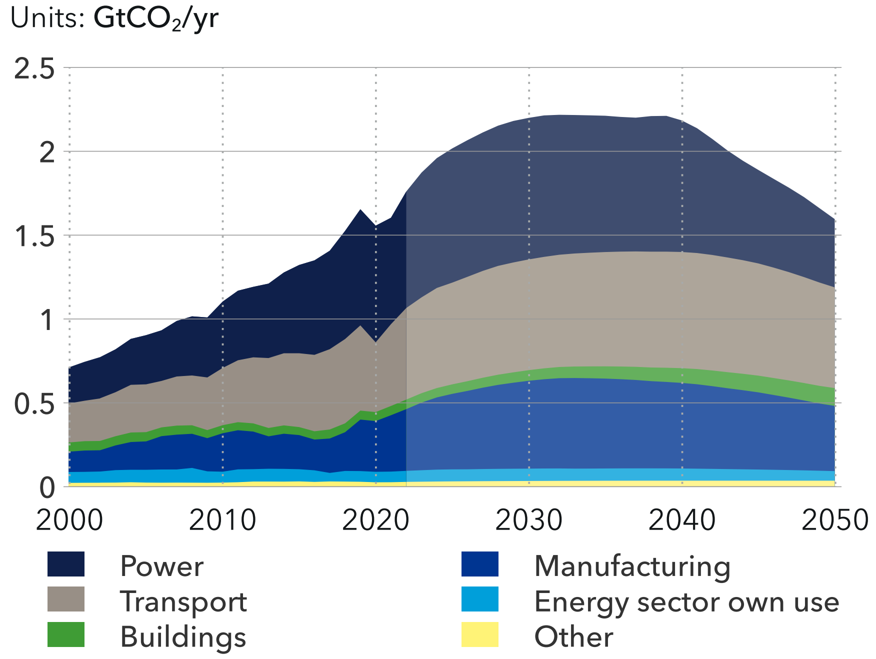
Although the regional average carbon price is comparatively low in the global landscape – projected to reach around USD 10/tCO_2 in 2030 – CCS initiatives are gaining momentum. Several of the large economies in the region have plans to implement different schemes and policies to support emissions reduction. Indonesia has around 15 potential CCS projects aiming to be operational by 2030, and Malaysia's state-owned oil and gas enterprise Petronas is proceeding with plans for a CCS hub. Natural gas production in Indonesia, Malaysia, and Thailand is a key sector for CCS application, given the existing infrastructure and favourable geological conditions, with several projects and regulations in development (PFI, 2024). Singapore has the most ambitious carbon tax plan in the region with steady increases until 2030. Further discussion of carbon pricing can be found in Chapter 6 of this report.

The annual energy-related CO_2 emissions from South East Asia are projected to plateau at 2.2 Gt in 2030 for around a decade, before declining to 1.6 Gt in 2050. Currently, coal consumption is the largest contributor to emissions, though our forecast underscores that oil emissions will match and then surpass coal emissions in the early 2040s. This trend reflects both the region's ongoing dependence on oil for road transport, and the ambitions to phase out coal in the 2040s in several large economies. Amongst end-use sectors, transport currently contributes the most emissions. This trend remains to 2050 when transport emissions will only be 5% higher than 2023. Figure 8.9.6 shows that manufacturing emissions will peak in the mid-2030s before declining 28% to 2050. This dynamic stems from our projections of accelerated electrification in manufacturing in contrast to the slower change in transport.

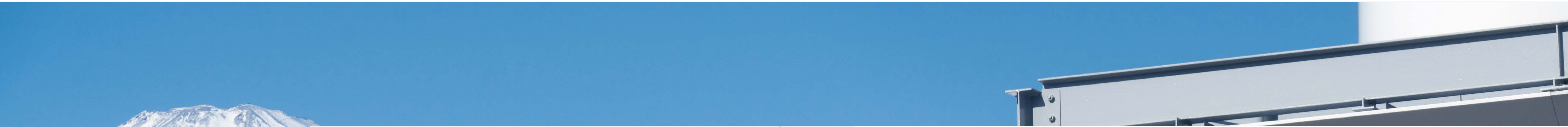
In the context of global climate policy, South East Asia's country pledges in NDCs imply a regional goal of restraining energy-related emission increases to no more than 378% by 2030 compared to 1990 levels. Discrepancies in targets and forecasts arise due to uncertainties concerning whether targets include non-energy-related CO_2 emissions. Our Outlook has energy-related CO_2 emissions increasing by 504% by 2030, suggesting that countries will fall short of meeting their pledges. Although some mid-century net-zero targets are enshrined in law, others lack a comprehensive policy plan to achieve them. Energy-related CO_2 emissions will be approximately 1.6 GtCO_2/yr in 2050, 15% below 2023 levels and around 28% lower than the projected peak emissions. This trend illustrates that while some progress will be made to reduce emissions in the region, policies and initiatives must be strengthened and deployed sooner to achieve net-zero targets.

FIGURE 8.9.6

South East Asia energy-related CO_2 emissions by sector



Historical data source: IEA WEB (2024)



8.10 OECD PACIFIC (OPA)

This region consists of Australia, New Zealand, Japan, and South Korea.

	Population (Million)	GDP* (USD Trillion) GDP/person (USD)	Energy use (EJ) Energy use/person (GJ)	Energy-related CO_2 emissions (Gt) Energy-related CO_2 emissions/person (tonnes)
2023	206	11.1 53 100	35.7 173.1	2.0 9.7
2050	189	13.7 72 300	26.1 138.0	0.4 2.0

*All GDP figures in the report are based on 2017 purchasing power parity and in 2023 international USD

8.10 OECD PACIFIC (OPA)

Current position

Countries have mature economies but diverse resource situations. Australia has abundant natural resources, New Zealand imports petroleum products, and Japan and South Korea have export-oriented industrial bases but are both energy-resource poor.

Bilateral relations are fostering transition efforts, including: Australia-South Korea's Comprehensive Strategic Partnership on clean energy technology and critical minerals, Japan-New Zealand's Strategic Cooperative Partnership, and Japan-Australia's partnership on Decarbonization through Technology.

Japan's energy supply remains stubbornly fossil-fuel dominated, at 87%. Renewables are constrained by geography and grids that require modernization to accommodate decentralized generation. Nuclear energy forms an important part of its energy mix.

South Korea relies on imports for close to 95% of its energy needs; its energy supply and power mix is fossil-fuel intensive at over 80% and around 59%, respectively (2023). It had 7% renewable and 27% nuclear shares in power generation in 2022.

Despite coal powering 54% of Australia's electricity, renewables – largely solar PV and wind – have made significant strides, accounting for 39% in 2023. Main GHG emission sources include electricity generation and mining, notably metal ore, coal, and oil and gas industries.

New Zealand had 44% of primary energy supply and over 80% electricity from renewables in 2022, primarily hydro, geothermal, and wind. Significant emissions originate from agriculture and energy sectors, and industry.

The region's energy-related CO_2 emissions have peaked and all countries have 2050 net-zero commitments.

Climate-related events are increasing in frequency: Australia fires cost USD 20bn (2021) and typhoon-related extreme rains in Japan and floods in New Zealand (2023) had losses of USD 2.9bn (Munich RE, 2024).

Pointers to the future

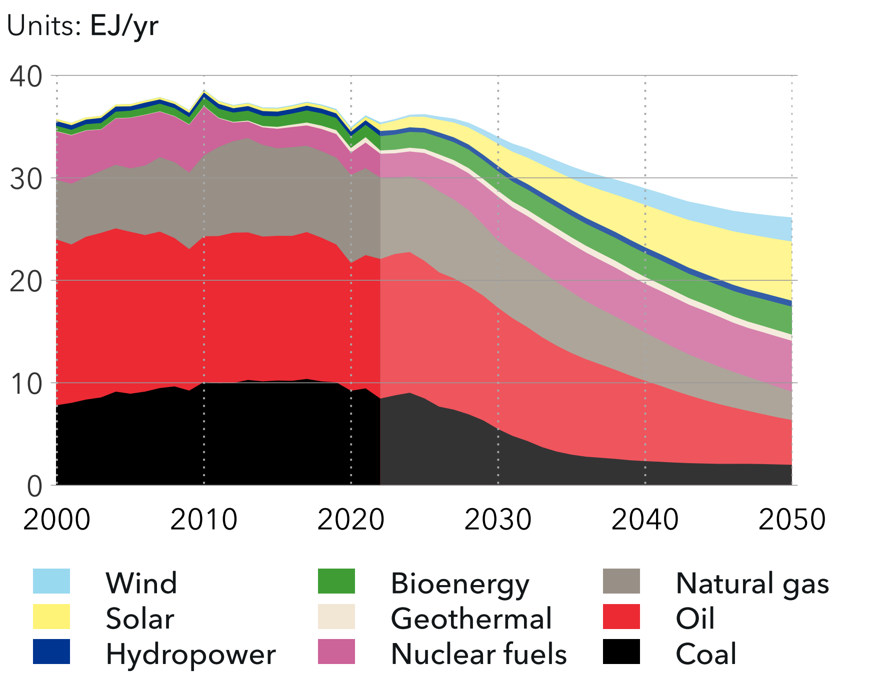
- Japan's revised *Basic Strategy for Hydrogen* (METI, 2023) includes a low-carbon hydrogen emission threshold of 3.4 kg CO_2e/kg-H_2 produced. A USD 20bn funding package underwrites a 15-year CFD subsidy to producers. CCS projects to realize the goal of 120 Mt/yr to 240 Mt/yr by 2050 announced with 13 Mtpa total CO_2 storage, commissioned by 2030. Target of 10 GW offshore wind by 2030 and 30 to 45 GW by 2040.
- South Korea targets 1.9 Mt/yr hydrogen supply/use by 2030, 5 Mt/yr by 2040, and a 7% share in the energy mix by 2036. It introduced an emissions-intensity standard and certification scheme. A clean-hydrogen power auction (June 2024) made 15-year PPAs available to build the market, shortlisting 26 companies (24 foreign suppliers) to provide hydrogen from 2028. Demand is stimulated in mobility and industry. *The Offshore Wind Power Competitive Bidding Roadmap* aims for over 18 GW by 2030 and up to 8 GW between 2024 and 2026 (tendering during fall 2024).
- Australia's emission reduction incentives include the *Safeguard Mechanism* for major GHG emitters, investment in transmission infrastructure, offshore wind (25 GW planned) and a *Capacity Investment Scheme* to support 23 GW additional renewable and 9 GW dispatchable capacity. It targets 82% renewable electricity by 2030. USD 15bn is allocated towards renewable hydrogen, critical minerals processing, green metals, low carbon liquid fuels, batteries, and solar manufacturing.
- New Zealand prepares its second economy-wide emissions reduction plan, covering 2026 to 2030. New legislation fast-tracks approvals for new infrastructure. Actions to address the expected decline in gas supply include possibly ending the previous government's embargo on oil and gas exploration.

Intra-regional dependencies

The region we define as OECD Pacific differs from other regions in that the countries are all industrialized but do not share common borders or connected power grids. This means that intra-regional energy trade by means of grid is not possible. Also, population density, energy resources and infrastructure vary greatly from Japan's north to New Zealand's south. Even so, there are commonalities. These include a growing focus on decarbonization and energy security combined with access to abundant wind resources and plenty of coastlines to capitalize on the growing offshore wind market. However, to complement variable wind and solar, the region's East Asian countries (Japan and South Korea) will increase the share of electricity generation from the use of nuclear – a clear measure of increasing their energy security.

FIGURE 8.10.1

OECD Pacific primary energy consumption by source



Historical data source: IEA WEB (2024)

The countries included in the OECD Pacific region have the smallest population of all regions and represent less than 3% of world population. The two most populous countries in the region, Japan and South Korea, also have one of the world lowest birth rates, which means that OECD Pacific region will have the fastest population decline at 9% towards 2050. To sustain high levels of prosperity, the region is investing heavily in research and development of new energy technologies, including next-generation batteries, smart grids, and carbon-recycling technologies. The aim is to maintain a position in energy technologies and to create new economic opportunities.

Deployment of new energy capacity is pointing towards making economies less dependent on primary energy, reducing energy intensity of the economy by 70%. Total energy use declines towards 2050, but electricity based primarily on renewable energy and nuclear increases its share from 25% to 42% by 2050. This change, together with other decarbonization efforts as well as energy system efficiencies, creates a noticeable change in the primary energy mix (Figure 8.10.1).

Energy trade

Australia, Japan, and South Korea have historically been heavily reliant on the trade of fossil fuels and raw materials – particularly iron ore, coal, and natural gas – to fuel their industrial and economic growth. Australia has been a major supplier of these resources, with its vast reserves of coal and iron ore being critical to the steel industries of Japan and South Korea. These two East Asian nations, in turn, have been significant consumers, importing large quantities of Australian coal and iron ore to sustain their heavy industries and energy sectors. Additionally, Australia is one of the world's largest exporters of LNG, supplying both Japan and South Korea with the natural gas needed to meet their energy demands.

The heavy reliance on fossil fuels is beginning to shift as the region aims to reduce carbon emissions and transition towards more sustainable energy sources. Developing renewable energy projects is central to this shift, particularly in Australia where there is a strong focus on solar PV development (ARENA, 2024). Australia is also leveraging its abundant solar resources to produce green hydrogen and ammonia, positioning itself as a future leader in renewable energy exports. These green energy carriers will play a crucial role in the future energy strategies of Japan and South Korea, as both nations have set ambitious targets for hydrogen in their energy mixes to achieve carbon neutrality.

The transformation in energy trade within this region is underpinned by a shift from traditional fossil fuels, such as coal and natural gas, to green energy carriers like hydrogen and ammonia, which will be produced in Australia and exported to Japan and South Korea. This intra-regional trade dynamic is set to evolve significantly as Australia expands its renewable energy capabilities.

For Japan, which remains one of the world's largest importers of LNG, the transition towards hydrogen is critical. Japan has revised its hydrogen strategy (METI, 2023) to include a significant role for imported hydrogen and its derivatives, which will be used to decarbonize its energy sector and industries such as steel manufacturing, where it will replace coking coal. South Korea, similarly, has ambitious plans to establish itself as a leader in the hydrogen economy by 2040, reducing its reliance on LNG and other fossil fuels (Carroll, 2024).

The trade of green hydrogen and ammonia from Australia to Japan and South Korea represents a new phase in the region's economic integration where renewable energy becomes the cornerstone of intra-regional trade. This shift will reduce the carbon intensity of the energy consumed in the region with over 70%, helping the regions countries to meet their decarbonization targets and contribute to global climate goals.

Solar explosion and wind expansion

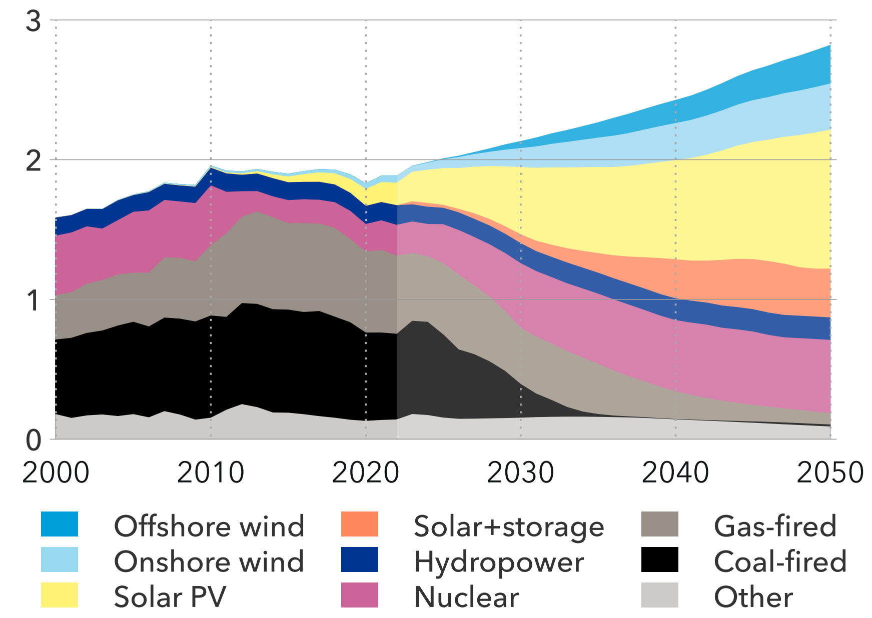
The region will see significant growth in renewable energy. Much of this capacity is utility-scale solar PV, often including storage, which will be mainly installed in Australia. Rooftop solar will find applications in all countries in the region, but in Australia and New Zealand the floor area per household is larger than that of Japan and South Korea, which limits rooftop availability for the East Asian countries. In Australia, rooftop solar generates over 10% of the electricity (Clean Energy Council, 2024). By 2023, 170 GW of solar, including some with storage, had already been installed. Capacity additions will continue to grow throughout the forecast period, peaking in the mid-2040s at over 45 GW per year. Thus, by 2050 the OECD Pacific region will have a 1 TW of Solar PV capacity installed, generating 1.35 PWh by 2050.

Wind, initially onshore and then offshore from the mid-2020s, will grow considerably. Australia's first floating wind farm was awarded a 2 GW license in 2024 (Vorrath, 2024) and an ambitious Japanese expansion aims for 10 GW by 2030. So far, auctions have been finalized and awarded 1.7 GW of bottom-fixed capacity, with more GW sized projects in the pipeline. By 2030 we expect just over 80 GW of wind capacity in OECD Pacific, which is almost four times more than today, growing to 215 GW in 2050. Just under 40% of that will be generated offshore. By 2050, 78% of on-grid electricity will be based on renewable energy and another 19% comes from nuclear power generation (Figure 8.10.2). The region will see continuous additions of nuclear capacity coming online during the forecast period, both from existing nuclear that has been temporarily shut down, and from new capacity to be built (Stapczynski, 2024). Nuclear supplies the region (Japan and South Korea) with 226 TWh of nuclear electricity in 2023, which will more than double to 524 TWh by 2050. While there are discussions in Australia on new nuclear, we do not foresee Australia introducing nuclear power in their mix within our forecast period to 2050.

FIGURE 8.10.2

OECD Pacific grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: GlobalData (2024), IRENA (2024), IEA WEB (2024)

Transport in transition

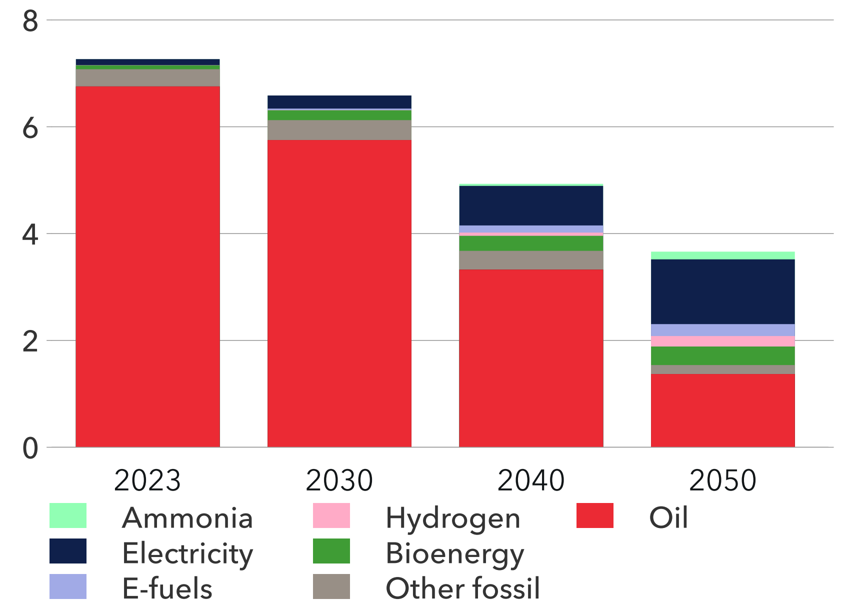
All the countries in the region are in essence island nations (South Korea has a closed border to the Democratic People's Republic of Korea). Thus, all the countries are dependent on shipping and aviation to import and export goods. Air travel demand has seen a drop since the pandemic and will not recover to the same level until 2029. However, we expect continuous growth towards 2050 and higher energy demand with it. Policies for reducing emissions in the aviation sector will have an impact on and reduce the energy mix from today's almost 100% oil-based to almost 40% sustainable aviation fuel by 2050. This will be supported by initiatives on carbon pricing and mandates in South Korea (Korea Times, 2024). In contrast to aviation, maritime shipping energy demand will decline significantly towards 2050, with higher shares of low emission fuels. Energy demand will decline slightly towards 2030 and then accelerate until 2050, when it will be 50% lower than its 2024 peak. By 2050, the maritime fuel mix will only be 42% fossil-based with the rest based on low carbon fuels and only 4% on electricity. Ammonia will probably be the main carrier, its uptake will be most prevalent after 2040.

The region has likely already reached peak vehicles, and road transport demand from a shrinking population will decline. Today the region has about 130 million vehicles, almost 80% of them providing passenger transport. By 2050 there will only be 83 million vehicles, and over 80% of those will be electric. EV sales are not as fast as in Europe or China, but will pass 50% of all new sales by early 2030s for passenger and late 2030s for commercial vehicles; part of the reason for this slow uptake is population density and slower growth of charging infrastructure. Even so, the EV uptake greatly impacts the energy demand and energy mix towards 2050. Road transport energy demand will be almost 60% electric, 9% based on hydrogen, and the rest using fossil fuels. The end result is a decline in energy demand of two thirds. In a region where 70% of overall energy demand comes from road transport, this is bound to have a major influence on the transport energy mix. The region will transform its transport system from being based primarily on oil and gas to being only 42% fossil-fuel based with the rest running on electricity (34%), bioenergy (9%), and hydrogen and its derivatives (15%) (Figure 8.10.3).

FIGURE 8.10.3

OECD Pacific transport energy demand by carrier

Units: EJ/yr



Other fossil includes natural gas and coal. Historical data source: IEA WEB (2024)

Hydrogen and its derivatives

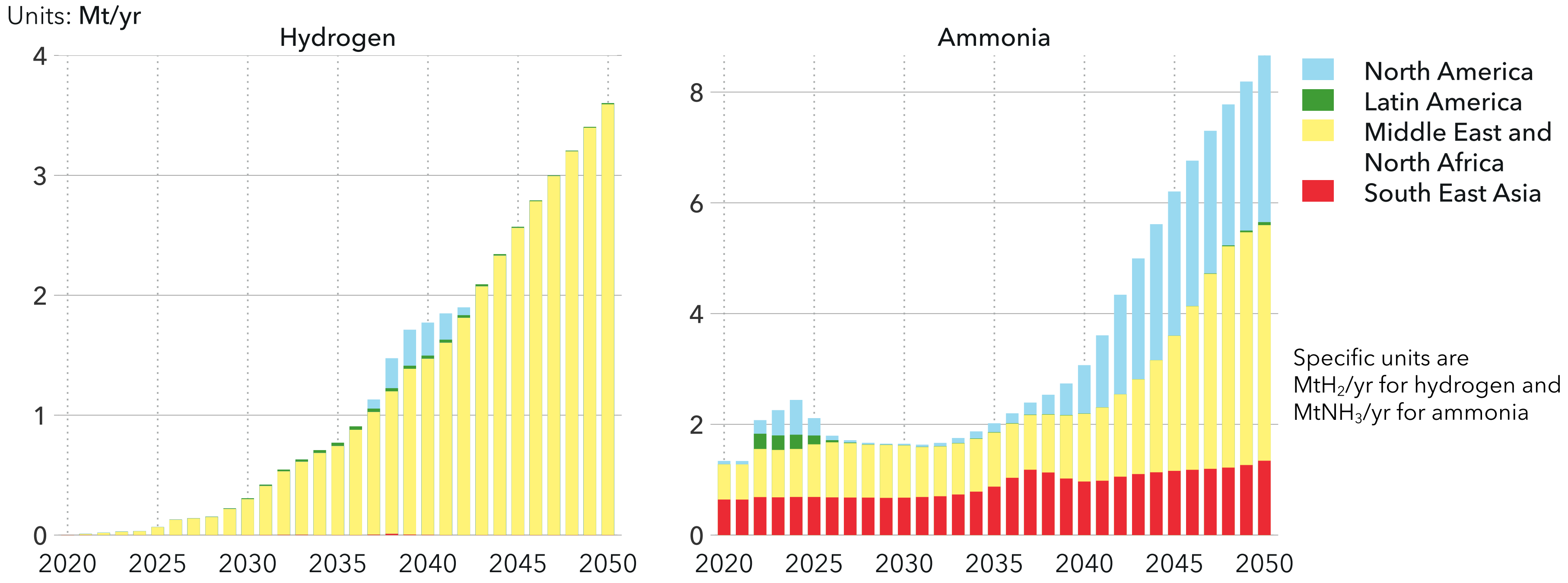
OECD Pacific countries not only have the highest share of hydrogen (including derivatives) of all the regions in the transport sector, but are expected to be at the forefront of hydrogen production (Australia) and use (Japan and South Korea) as an energy carrier. Hydrogen and its derivatives will represent around 7% of the final energy demand in the region by 2050, the third highest share after Europe and North America. Today, hydrogen's role in the region is primarily in refineries. By 2050 the manufacturing sector (37%), refining (16%), and synthetic fuel production (16%) will represent the biggest users of total hydrogen demand.

There will also be almost 1 Mt of hydrogen used for power generation, representing 6% of total hydrogen demand. While we do not model intra-regional trade, we anticipate much of the hydrogen produced will be from dedicated solar PV-based electrolysis plants in Australia, combined with production from grid-connected electricity based on renewables. Much of the derivatives such as ammonia and e-fuels will be transported to South Korea and Japan for use in manufacturing, refinery, power, and transport and in some instances converted back to hydrogen for electricity generation.

Hydrogen demand more than doubles from less than 8 Mt in 2023 to 15 Mt in 2050. Hydrogen demand will mainly come from Japan and South Korea, whereas supply largely is based in Australia. In addition to intra-regional trade with hydrogen transported from Australia, we foresee 3.5 Mt exported from the Middle East and North Africa. Ammonia and methanol demand will also see growth trajectories equivalent to those observed in hydrogen and will represent about 10 and 13 Mt each in annual demand by 2050, for which most is used as an energy carrier. However, production capacity for ammonia will be limited to only 3 Mt annually and thus OECD Pacific will turn to imports to satisfy growing demand. For ammonia, this would mean 8 Mt/yr imported by 2050 (Figure 8.10.4).

FIGURE 8.10.4

OECD Pacific hydrogen and ammonia imports by source region



Emissions

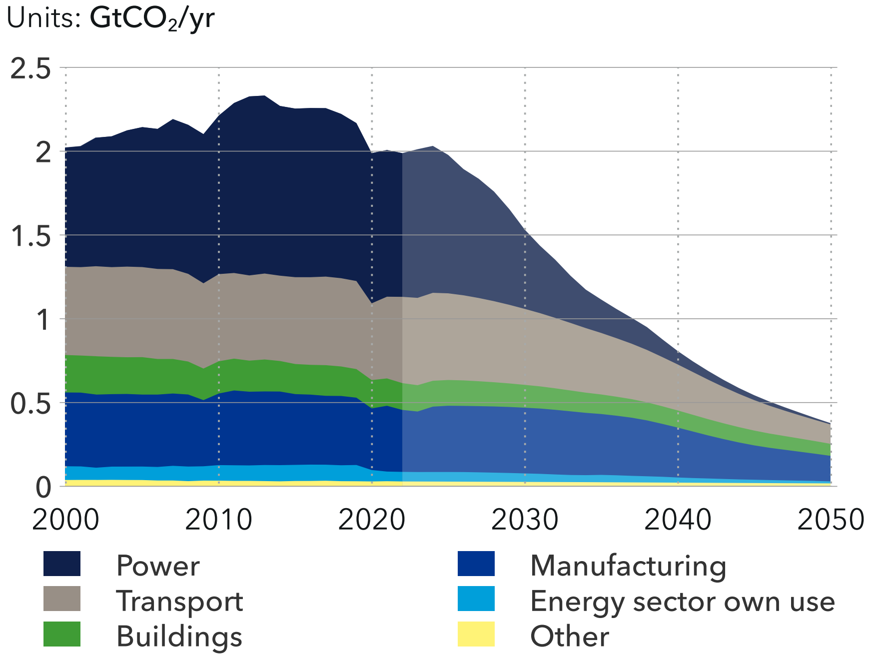
Declining primary energy use, combined with declining population, will lead to emissions falling continuously during the forecast period. All sectors reduce their emissions, but the fastest rate will be from reducing coal use in the power sector, declining 99% from 2023 to 2050. Most of the remaining energy-related emissions in 2050 will be found in the manufacturing sector from energy (40%), which will decline by 58% to 2050. The transport sector is the second largest source of emissions, representing 31% in 2050, and which will see a 78% decline by 2050. Overall, looking at the energy carriers, natural gas will represent 29% of the emissions in 2050, while oil reaches 43%, and coal has the largest decline goes to 25%.

The OECD Pacific country pledges in NDCs aspires to a regional target of reducing energy-related CO_2 emission by 13% by 2030, relative to 1990. However, our forecast indicates that OECD Pacific energy-related emissions will only decrease 6% by 2030 compared to 1990 levels, indicating that the region will not meet its targets. New Zealand was first in the region to enshrine in law its 2050 net-zero emission target (non-agricultural activities) in 2019, followed by Australia in 2021. South Korea and Japan have pledged carbon neutrality by 2050. For the region, energy-related CO_2 emissions are expected to be 0.4 $GtCO_2$ per year (net of DAC) in 2050, 77% below 2023 levels, but still not meeting the net-zero emission targets (Figure 8.10.5).

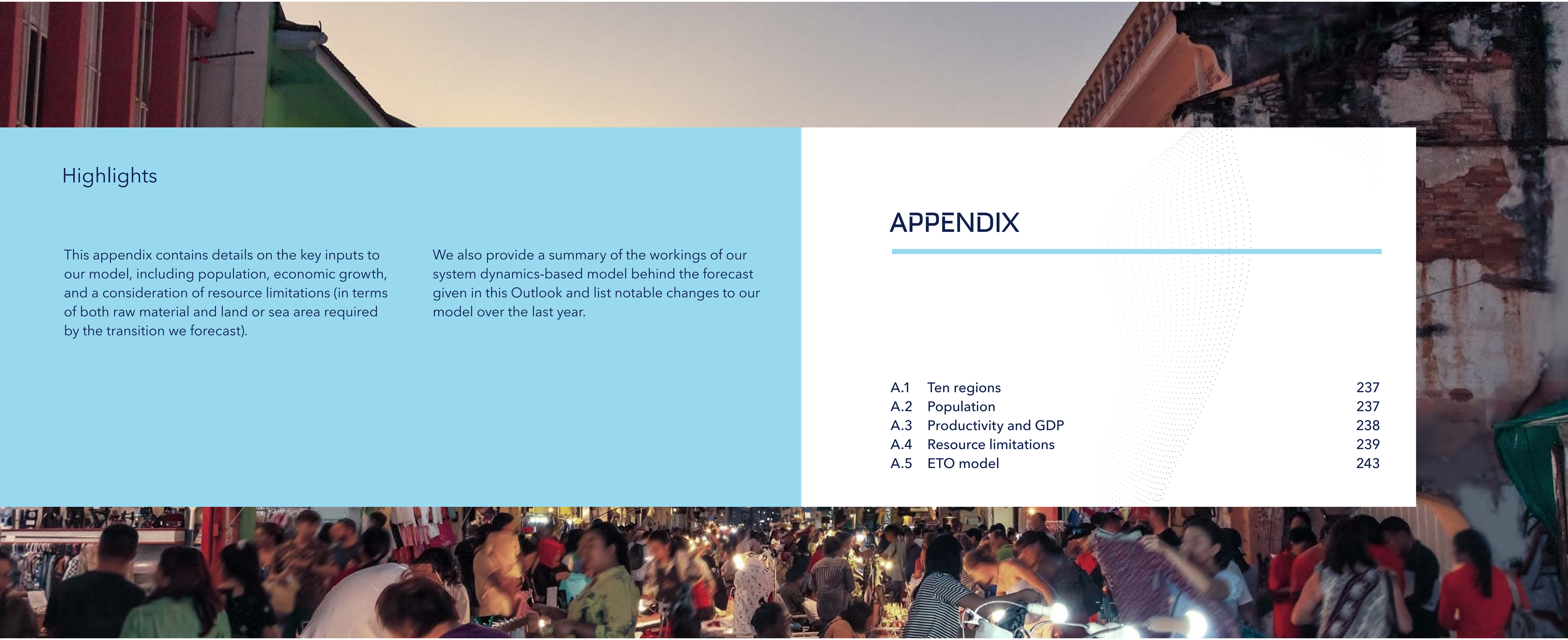
Our projection for the regional average carbon-price level is USD 35/tCO_2 in 2030 and USD 130/tCO_2 by 2050. Carbon pricing will play an important part of the policy mix to achieve net-zero 2050 targets adopted by all countries in the region (Section 6.3). The number of captured emissions amounts to 140 $MtCO_2$ or 10% of globally captured CO_2 emissions. In addition we expect another 16 $MtCO_2$ to be captured from the atmosphere through negative emission technologies.

FIGURE 8.10.5

OECD Pacific energy-related CO_2 emissions by sector



Historical data source: IEA WEB (2024)



Highlights

This appendix contains details on the key inputs to our model, including population, economic growth, and a consideration of resource limitations (in terms of both raw material and land or sea area required by the transition we forecast).

We also provide a summary of the workings of our system dynamics-based model behind the forecast given in this Outlook and list notable changes to our model over the last year.

APPENDIX

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A.3 Productivity and GDP 238
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A.1 TEN REGIONS

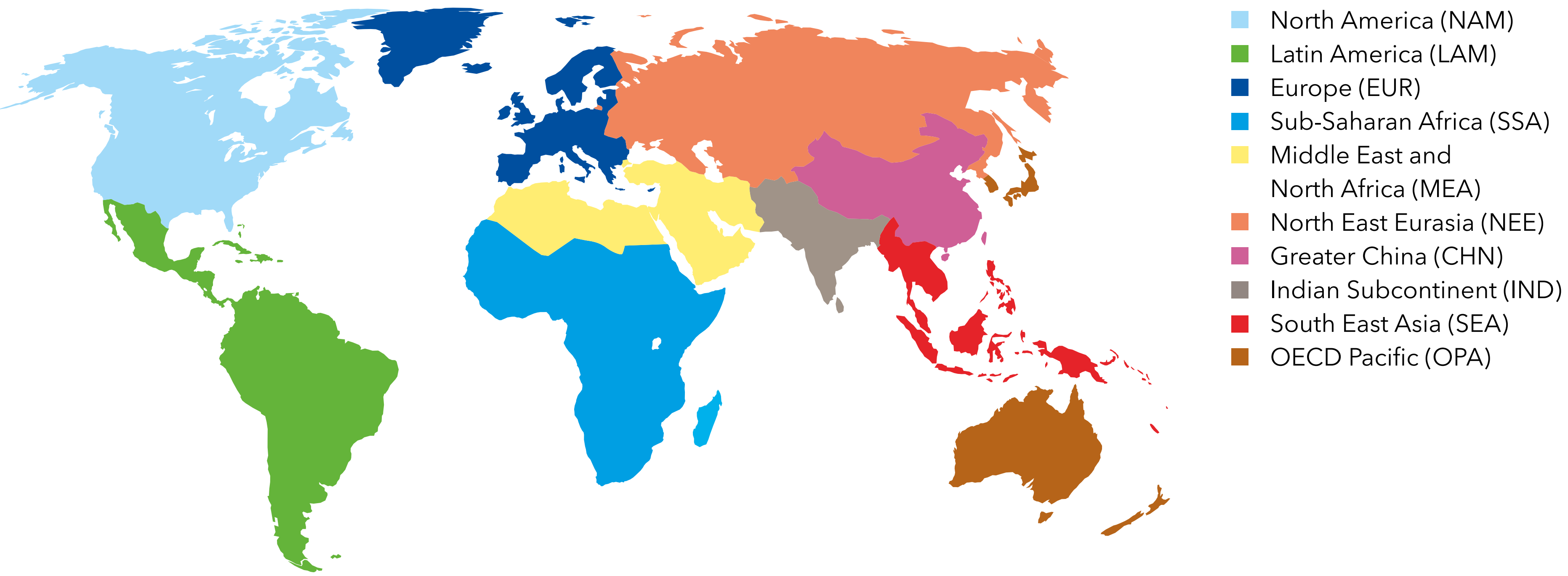
In this Outlook, we have divided the world into 10 geographical regions. These regions are chosen based on geographical location, extent of economic development, and energy characteristics.

Each region’s input and results are the sum of all countries in the region. Where relevant, weighted averages are used, such that countries are assigned weights relative to population, energy use, or other relevant parameters. Distinctive characteristics of certain countries - for example, nuclear dominance in France – are thus averaged over the entire region.

In a few places, we refer to ‘OECD regions’; this comprises the three regions North America, Europe, and OECD Pacific. We also use the terms ‘high income’, ‘middle income’ and ‘low income’ countries and regions, broadly in line with the definition established by the World Bank (Prydz et al., 2019).

Detailed discussions, results, and characteristics of the regional energy transitions are included in Chapter 8 of this Outlook, which presents regional analyses and forecast energy transitions for each of the ten world regions.

FIGURE A.1



A.2 POPULATION

A typical energy forecast starts by considering the number of people that need energy. Although energy consumption per person varies considerably, and will continue to do so, everyone requires access to energy in one form or another.

We usually base our population data and projections on data from the UN Department of Economic and Social Affairs, which publishes its World Population Prospects, normally every other year. The forecast in their latest update, published in July 2022, runs to 2100. We also consider data from other entities that separately produce population forecasts, including the US Census Bureau and the Wittgenstein Centre for Demography and Global Human Capital in Austria.

The Wittgenstein Centre has a stronger emphasis than the UN on how future education levels, particularly among women, will influence fertility. As noted by Lutz (2014), urbanization in developing countries will result in fertility rates falling; having many children is a greater economic burden and less of a necessity in cities than in traditional, rural settings. Furthermore, evidence indicates that higher levels of education among women are associated with a lower fertility rate (Canning et al., 2015). Sustainable Development Goal (SDG) #4 Quality Education and SDG #5 Gender Equality are providing further impetus to improving female education.

Fertility is low in both the OECD and China, and is falling considerably in non-OECD regions. In Sub-Saharan Africa (SSA), the reduction in fertility has been slower than in other parts of the world; the total fertility rate is still at about 4.5 births per woman, falling by about 0.6 births per woman per decade. SSA, where

many of the low-income countries are located, also lags other regions in education expansion. However, we assume that urbanization and improved education levels among women will, eventually, also accelerate the decline in fertility rates in Africa.

The Wittgenstein Centre uses several scenarios related to the five different 'storylines' that were developed in the context of the Inter-governmental Panel on Climate Change, IPCC (van Vuuren et al., 2011). The IPCC calls these storylines 'Shared Socio-economic Pathways (SSPs)'. In this Outlook, we follow the central scenario (SSP2) for population and use it as a source of inspiration for other forecast inputs.

Using the Wittgenstein population projections for SSP2, we arrive at our 2050 population forecast of 9.6 billion. This is an increase of 17% from today's population of 8.2 billion (UN, 2024). By mid-century, the global population will still be growing, but the rate is reduced to 0.4% per year and SSA will be the only region with notable growth.

Our 2050 figure of 9.6 billion is 4% lower than the latest UN median estimate of 9.7 billion. Had we used the UN median population projection, most of our energy demand figures would have increased commensurately, but with regional variations. However, the difference is minor. The main uncertainty lies in the long term (2100 and beyond) forecast, where most mainstream forecasts, including the UN's, now indicate global population will peak before 2100.

A.3 PRODUCTIVITY AND GDP

GDP per capita is a measure of the standard of living in a country and is a major driver of energy consumption in our model. From a production point of view, it is also a good proxy for labour productivity, as it reflects the amount of economic output per person.

We base our GDP per capita forecast on the GDP per capita growth rates implied by the latest update of World Economic Outlook by IMF (2023) until 2028 and then on the GDP per capita growth rates implied by the OECD (2023) and International Institute for Applied Systems Analysis (IIASA) projections through 2050.

With the updated data, the general trends in productivity improvements and relative positions among the regions remain similar to the ones in our forecast last year. The fastest growth in GDP per capita between 2022 and 2030 will still be in Asia. The Indian Subcontinent (IND) will have the highest growth rate at an average of 4.8%/yr, followed by Greater China (CHN) at 3.9%, and South East Asia (SEA) at 3.6%/yr (Figure A.2).

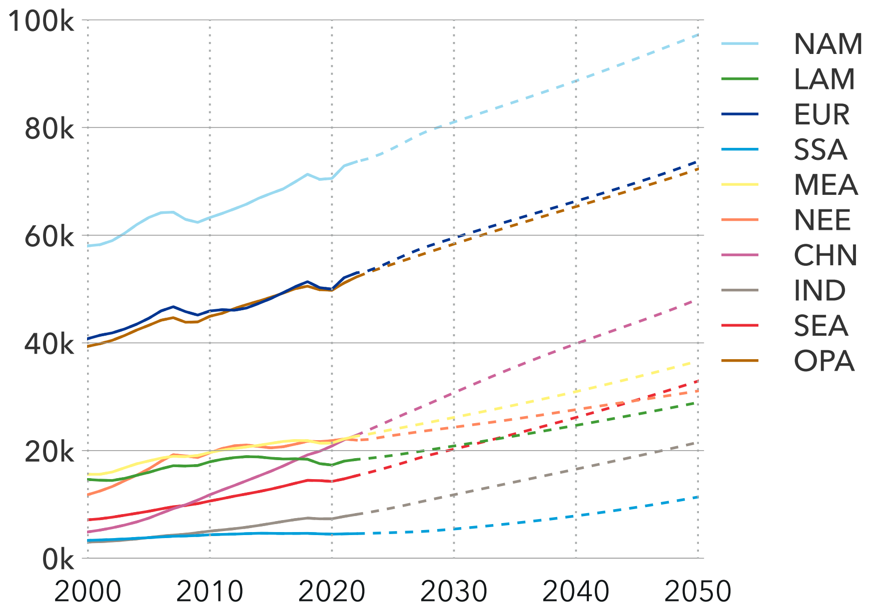
As these economies mature, growth in GDP per capita will slow down after 2030. The period between 2030 and 2050 will be characterized by a more-even spread of prosperity improvements globally, with the highest growth in the low-income regions. SSA will see the fastest GDP per capita growth with a CAGR 3.98%/yr, followed by IND at 2.7%/yr. Improvements in the standard of living in economically developed regions will reduce to 1.1%/yr or lower in the 2040 to 2050 period. The forecast beyond 2030 does not include any larger changes in the relative positions of productivity in the different regions.

World GDP is expected to grow from USD 169trn/yr in 2023 to USD 320trn/yr in 2050. This near doubling over the 27-year period is a result of a 20% increase

FIGURE A.2

GDP per capita by region

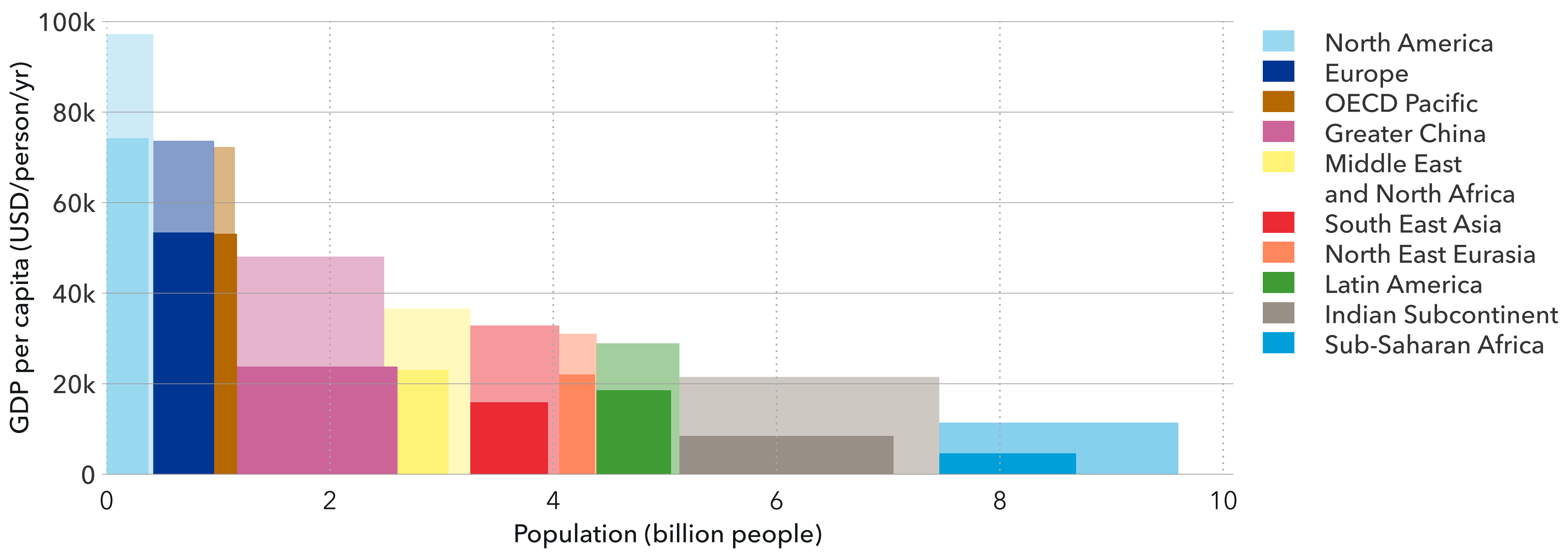
Units: USD/person/yr



Historical data source: OECD (2021), UN (2022), IMF (2024), WIC (2023)

FIGURE A.3

Change in population, GDP per capita and GDP between 2023 and 2050 by region



Darker boxes represent 2023, lighter boxes represent 2050. Historical data source: OECD (2021), UN (2022), IMF (2024), WIC (2023) in population and a 58% increase in average GDP per capita, with large regional differences. Figure A.3 illustrates the combined effect of population change (x-axis) and GDP per capita growth (y-axis); the decadal growth figures are included in Table A.1.

The world experienced a 1.9% compound annual GDP growth from 2000 to 2020 (Table A.1). In the 2040s, this will gradually slow to 1.5%/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, albeit at varying rates, with likely exceptions only in mature economies that are experiencing marked population decline, such as Japan.

> Most economies around the world will continue to grow, albeit at varying rates, with likely exceptions only in mature economies.

TABLE A.1

Compound annual GDP growth rate by region (in %)

		2000-2020	2020-2030	2030-2040	2040-2050	2020-2050
NAM	North America	0.85	1.60	0.91	0.93	1.15
LAM	Latin America	0.69	2.08	1.70	1.60	1.80
EUR	Europe	0.93	1.98	1.10	1.06	1.38
SSA	Sub-Saharan Africa	1.51	1.86	3.78	3.76	3.13
MEA	Middle East and North Africa	1.46	2.15	1.70	1.70	1.85
NEE	North East Eurasia	3.16	1.25	1.27	1.19	1.24
CHN	Greater China	7.47	4.19	2.68	1.91	2.93
IND	Indian Subcontinent	4.44	5.00	3.50	2.68	1.91
SEA	South East Asia	3.51	3.55	2.60	2.33	2.83
OPA	OECD Pacific	1.13	1.69	1.14	1.02	1.28
	World	**1.90**	**2.34**	**1.67**	**1.51**	**1.84**

A.4 RESOURCE LIMITATIONS

During the coming three decades, there will be a profound shift in the type and amount of new capacity added to the energy system on both the supply and demand sides. The energy system has relied on fossil sources ever since the Industrial Revolution, but it is now heading for an energy mix where electricity, renewables, and batteries represent 50% of the primary energy system by 2050. This shift will not only impact the type of energy sources in the energy system, but there will be large shifts in demand for surface area and raw materials to support the transition. Coal mines will shutter, oil demand will face a peak and decline with over 30%, while nickel and lithium mining will boom. Instead of growing oil and gas extraction from offshore platforms, there will be solar panels and turbines harvesting sun and wind resources for energy with increasing amounts of batteries in electric vehicles (EVs) and grids to store the energy.

One central feature of our forecast is the increasing rate of electrification of the world's energy system. Electricity and energy stored in batteries will increasingly power road transport. In 2050, there will be 1.3 billion passenger EVs on the road. Transitions on this scale require sufficient raw materials to build the infrastructure and end-use technology. Natural resources supply must be capable of expanding at rates that can support demand sustainably and cumulatively. Although we expect there will be local resource demand challenges and price volatility in the future, the overall picture is that there are enough raw materials and land to support the transition.

A.4.1 Raw material demand from batteries

The rapid global adoption of EVs is a key trend highlighted in DNV's *Energy Transition Outlook*. EVs are central to many region's decarbonization strategies in road transport. A significant driver of this growth is the steep decline in battery costs, which fell by 90% in the last 15 years (DOE, 2024). Additionally, batteries with chemistries like those used in EVs, such as lithium-ion, will become increasingly important for future energy grids to balance renewable supply and demand. But, with this growth comes the challenge of securing a reliable supply of essential minerals for battery production. Can the mining industry, battery manufacturers, and regions collaborate and collectively secure enough supply for battery materials?

The upstream supply chain is under significant pressure as demand for essential minerals – particularly cobalt, nickel, and lithium – is rapidly increasing. These minerals are attracting heightened attention from both governments and industry due to the challenges in securing a stable supply to meet the exponential growth in demand. This has led to significant swings in commodity prices in recent years and increased competition between companies and countries to address supply bottlenecks.

Policymakers are acutely aware of the upstream squeeze and are advancing plans to build regional battery supply chains. Regional upstream and midstream elements (mining and refining) are much less advanced. Several projects are under way, but long permitting times coupled with a general pushback against new mining projects will automatically create a gap between domestic demand and supply.

The necessity of mining is often cited as a drawback of the transition to EVs – big spades replacing big oil. But unlike fossil fuels, there is no material loss during the battery lifetime and all minerals can theoretically be recovered via a recycling process. As a result, recycling is an essential complement to the lack of mined resources to secure a long-term sustainable supply of batteries.

The forecast growth in battery capacity is by far the largest driver of demand for minerals. We expect the biggest supply challenges in lithium, nickel, and cobalt used in Lithium-ion battery manufacturing.

Cobalt
Based on our EV-growth forecast, we estimate the global demand for cobalt to be 280 kt/yr in 2030; 58% of this demand is for passenger vehicles, 37% for commercial vehicles, and 5% for two- and three-wheelers. Current annual extraction needs to increase 2.5 times to support this demand from 2023 to 2030.

Given the lack of space or weight constraints, we do not foresee battery chemistries that include cobalt being used for grid-connected stationary batteries. Moreover, the geographical concentration of cobalt mines (about 70% of production is in the Democratic Republic of Congo) further incentivizes all battery producers (including EV batteries) to explore new and cobalt-free battery chemistries (Northvolt, 2024).

Lithium
Total global lithium production was around 200 kt in 2023 (Our World in Data, 2024), and demand from EV and grid batteries constituted about 60% of the lithium production. Based on our Li-ion battery growth forecast, lithium demand will reach a total of around 460 kt/yr by 2030. Despite growing installations of grid-connected batteries, EV batteries will continue to dominate the lithium demand, with a 93% share in 2030 and 85% in 2050. Going forward, we forecast that lithium demand for both battery types to increase to around 1050 kt/yr by 2050, a two-fold growth.

We do foresee some challenges in scaling up lithium processing capacity to keep pace with this forecast demand growth: Purification plants are capital-intensive and current processing plants are concentrated in certain locations around the world (European Commission, 2024). Nevertheless, the stable demand forecast will aid in lithium market reaching hitherto non-existent maturity, especially with the clear signals from battery manufacturers and OEMs. Lithium mining and processing will start attracting more interest as more forward-looking, long-term contracts are awarded (Carbon Credits, 2024).

Nickel
In 2023, demand for nickel for EV and grid batteries amounted to 330 kt/yr, about 10% of the total demand for nickel. By 2030, we forecast this demand to increase to 560 kt/yr, a 70% increase from 2023 levels.

With our current assumptions, which include decreasing mineral intensity and the uptake of new chemistries, recycling can cover an increasing share of material demand. However, most of the input will still need to be mined because demand is growing exponentially.

> The overall picture is that there are enough raw materials and land to support the transition.

Conclusion
In our view, the availability and scaling of raw materials will not significantly constrain our forecast energy transition globally. However, narrowing the perspective, some regions may struggle to find raw materials while others will enjoy an abundance.

As we have seen, a continued push for new mining and refining capacity is the most important short- to mid-term activity. However, building a complete recycling ecosystem should be an essential part of each region's strategy for independent and resilient battery supply chains in the longer term. A continued expansion of recycling facilities can kickstart a sizeable scaleup of recycling capacity from production scrap in this decade and lay down the foundation for a growing domestic market for materials from end-of-life batteries. Realizing the full potential of battery recycling will require substantial support across the supply chain to avoid being limited by virgin material sources.

Historically, such imbalances would be solved by global collaboration and trade. The intensified focus on energy security also includes security of supply of critical resources, so many regions are reviewing their strategy and dependence on other regions to provide the raw materials necessary for securing their energy supply or transition. This will further augment existing imbalances and could affect costs in the short to medium term and thus warrants continuous monitoring.

A.4.2 Solar PV expansion

Surface area requirements
We forecast a twelve-fold increase in solar PV capacity (including off-grid) by 2050. Sufficient land and building area are prerequisites to support such expansion. In our model, solar PV is installed at utility scale, in microgrids, on the roofs of residential or commercial buildings, or off-grid as capacity to produce hydrogen. Utility-scale, microgrids, and off-grid capacity compete with other uses of land. In our Outlook, we forecast 17% of all solar PV will be installed on rooftops and commercial buildings globally. 12% of total capacity (2.2 TW) is further installed to support hydrogen production. An estimated regional average between 20 and 45 MW/km2 for non-rooftop solar PV installations requires less than 1% of total land area globally in 2050. Even for

regions with large shares of solar PV in their power mix, the land-area requirement is not unmanageable. For example, 1.5% of agricultural land in Greater China and South East Asia will be used for solar PV installations in 2050. Co-use of land for grazing or for certain types of agriculture is also possible. Therefore, it seems unlikely that the expansion of solar PV will encounter land-area limitations overall. We are also seeing a growing interest in and developments involving floating solar PV which can alleviate pressure on available land.

Raw material requirements

Different types of solar PV panels use different materials. Today and in the foreseeable future, we expect solar PV panels to continue to consist mainly of crystalline silicon cells (DNV, 2021) where the main components are silicon, steel, copper, and silver. All are considered abundant material (USGS, 2023), but we see a significant growth in demand towards 2050 as a result of our forecast increase in solar PV use. We account for the increased material efficiencies in our forecast of the material demand growth (Table A.2). Considering that silicon is abundant and all other solar PV components are only using a fraction of today's total demand (5% of copper and 13% of silver), we do not anticipate material requirements will be a limitation.

There are rapid strides being made in material intensity improvement when it comes to silver since it is a precious commodity. By 2030, we forecast that silver demand for solar PV panels will reach about 20% of 2023 global demand, but average silver intensity embedded in solar PV capacity around the world reduces by 15% over the same time. While there have been disruptions in silver mining capacity additions in the recent past, we do not foresee this to be a major issue for satisfying the increasing demand (Silver Institute, 2024).

There are no short-term limitations on processing facilities that enrich silicon to a high enough grade needed for photovoltaic panels. However, manufacturing capacity needs to continue to grow with increasing demand.

Lastly, new thin-film technologies, which are not yet prevalent but show potential, will further reduce the overall demand for silicon and other materials.

Solar panel recycling is a growing industry in certain niche geographical locations such as Australia. However, it has not taken root due to non-beneficial economics such as a lack of economies of scale and cheap raw material availability. In the near term, we foresee non-economic factors – such as concerns regarding waste disposal when the panels are retired – playing a role in the establishment of solar PV panel recycling. In the longer term, as more and more solar PV panels and plants near retirement age and the technology to recycle and recover silicon and other materials improves, solar panel recycling may also play a pivotal role in material provision for solar PV panel manufacturing.

TABLE A.2

Demand for selected clean technology minerals

Material type	Solar PV material demand in 2030 (indexed to 2023 solar PV material demand)	Solar PV material demand in 2050 (indexed to 2023 solar PV material demand)
Silicon	116%	270%
Copper	143%	256%
Silver	147%	247%

A.4.3 Wind expansion

Surface area requirements

We predict a six-fold rise in installed wind energy capacity by 2050. Will there be sufficient land and ocean-surface area for this expansion? Onshore wind has a relatively small footprint, effectively just the base of the tower, so there will be no lack of land area. However, the siting of tall, rotating structures in densely populated areas is a growing societal concern. In our analysis, we have reviewed the overall technical potential and only included areas with sufficient wind speeds while avoiding densely populated or ultra-remote locations. This year, we also included the effects of societal pushback as a construction time delay factor in some regions. Onshore wind experiences the largest delays. With this consideration and using an estimated area demand of 5 MW/km^2 giving almost 1 km of space between each turbine, all onshore wind farms cover a total of 1,000,000 km^2. This equates globally to less than 1% of available land. For comparison, this is about 2.2% of agricultural land. At the most extreme, the expected capacity represents 10% of the technical potential in South East Asia and much less in other regions. Thus, the limiting factor will not be the availability of land.

Rather, it will be peoples' collective acceptance of visual, noise, and other environmental and societal impacts associated with land-based wind power.

Offshore wind is located far from populations and provides plentiful energy in our Outlook. Our analysis and modelling include both fixed offshore wind and floating offshore wind in water depths exceeding 50 m. Globally, there will be enough sea area and coastline to accommodate the forecast amount of offshore wind. Europe and Greater China will account for 54% of global installed offshore wind capacity by 2050. We expect Europe and the North-Sea basin to install mostly fixed (86%) but also floating offshore wind. For Greater China, the mean water depth of 44 m off the region's coastline and in the Yellow Sea is well suited for fixed offshore wind, so 88% will be bottom fixed there.

Only a small fraction of the installations will be floating offshore wind, so it is fixed offshore wind that comes closest to reaching to technical capacity. The Indian Subcontinent will install 40% the technical potential of fixed offshore wind by 2050, the Middle East and North Africa will reach 38%, and several regions will reach 15% to 20% of their technical capacity. Looking at offshore wind overall, this means that Greater China will utilize almost 17% of its coastline for installing offshore wind. Growing concerns on biodiversity and other uses of the ocean will need to be managed to successfully install such large amounts of offshore wind. Offshore energy extraction, fishing, and the growing area of ocean-based food farming will need to collaborate successfully – and explore synergies – to ensure enough area is available for all parties to thrive.

Raw material requirements

Wind turbines and their supporting structures mostly use common building materials, but the vast amounts of steel and cement required will put pressure on those hard-to-abate sectors to reduce their embedded carbon footprint during production to ensure low lifecycle emissions from wind. In addition, there is some competition between other growing demand sectors for rare earth elements. These are, contrary to the name, abundant but expensive and resource-intensive to extract, especially in the case of the neodymium used for permanent magnets in the turbines and electric EV motors. However, neodymium is not a prerequisite for building turbines, generators, or EV engines and we are already seeing a diversification of technologies that use other magnetic materials, gearbox designs, or electromagnets.

The majority of the wind turbines are built from steel and concrete, which we consider abundant materials. Global steel production in 2023 was 1.9 billion tonnes (World Steel Association, 2024) and 110 GW of turbines were installed globally in 2023. This means wind turbine steel demand used less than 1% of global steel output. As more wind goes offshore and both structures and towers become bigger, there will be an increase in demand for steel. However, even with our forecast 5-fold increase in annual added capacity this would mean that only about 4% of global steel production output in 2050 will be used for wind installations. This would put the wind energy steel demand about the same as the automotive industry steel demand. Decarbonizing the production processes for cement and steel to ensure low life cycle emissions is far more important than reducing wind turbine steal demand.

> Even with our forecast 5-fold increase in annual added capacity this would mean that only about 4% of global steel production output in 2050 will be used for wind installations.

Offshore Wind Turbine Concrete base, Poland

A.5 THE MODEL

The Energy Transition Outlook (ETO) Model is a dynamic simulation tool developed to forecast the most likely trajectory of global energy systems from 1980 to 2050. This model leverages system dynamics principles to capture the complex interactions and feedback loops within the global energy system, ensuring a comprehensive understanding of how various factors influence one another over time.

The model represents the energy system through interconnected modules (Figure A.4). These include:

- **Final energy demand:** Covering sectors such as buildings, manufacturing, transport, and non-energy applications.
- **Energy supply:** Encompassing the production of coal, gas, oil, and bioenergy.
- **Transformation processes:** Including power generation, oil refining, and hydrogen production.

Additionally, the model integrates broader variables like economic conditions, grid infrastructure, carbon capture and storage (CCS), energy markets, trade volumes, and emissions. These modules continuously interact, exchanging data on demand, costs, and other key parameters to produce a coherent, integrated forecast.

Principles of system dynamics

At the heart of the ETO Model lies the system dynamics approach, which focuses on understanding how complex systems evolve over time through feedback loops, accumulations (stocks), and delays. This approach is particularly suited to modelling the global energy system, which is characterized by significant inertia, non-linearity, and interconnectedness. For example, a change in solar PV technology adoption can ripple through the system, affecting coal demand, shipping volumes, and oil consumption in maritime sectors.

The model's feedback-driven nature ensures that no single element operates in isolation. Instead, all components are part of a tightly interwoven system where the output of one module influences the inputs of others. This approach reflects the real-world behaviour of energy systems where decisions and changes propagate across sectors and regions in non-linear ways.

Granularity and data-driven insights

The ETO Model operates at a global scale but is divided into 10 distinct regions, each interacting through energy trade and shared global variables. This division allows us to capture regional differences and the variability inherent in global energy systems. The model uses statistical distributions for certain parameters, such as investment costs, to reflect the diverse conditions across regions. This granular approach ensures that the model provides detailed insights while maintaining a comprehensive view of the global energy transition.

The model’s granularity is further enhanced by its data-driven foundation. Parameters and equations are sourced from a wide array of reputable databases and reports, including IEA’s World Energy Balances, GlobalData Power Database, and UN Comtrade. These inputs are supplemented by insights from nearly 100 DNV experts to ensure that the model accurately reflects the complexities and nuances of real-world energy systems.

Focus on long-term trends and robustness

The ETO Model is designed to capture long-term dynamics over decades, making it particularly well-suited for studying energy transitions. Operating as a continuous-time model, it tracks annual changes in energy systems, though short-term fluctuations are incorporated indirectly through aggregated parameters. This long-term focus allows the model to generate robust forecasts that consider the gradual evolution of energy markets, technology adoption, and policy impacts.

In line with system dynamics principles, the model does not assume equilibrium or optimality. Instead, it simulates how energy systems evolve over time based on existing inertia, delays, and non-linear interactions. For instance, the model incorporates behavioural economics insights, acknowledging that private vehicle buyers may prioritize upfront costs over total ownership costs, leading to different adoption rates for new technologies across different consumer segments.

Transparency and adaptability

A key strength of the ETO Model is its transparency and adaptability. We regularly conduct sensitivity analyses to test how changes in key inputs – such as GDP growth rates or technological learning curves – affect the model's outputs, ensuring that the forecasts are both robust and transparent.

Moreover, we regularly update the ETO Model to reflect the latest data and trends, making it a dynamic tool that evolves alongside the global energy landscape. This adaptability ensures that the model remains relevant and accurate to provide stakeholders with up-to-date insights into the pace and nature of the energy transition.

> This model leverages system dynamics principles to capture the complex interactions and feedback loops within the global energy system, ensuring a comprehensive understanding of how various factors influence one another over time.

This model leverages system dynamics principles to capture the complex interactions and feedback loops within the global energy system, ensuring a comprehensive understanding of how various factors influence one another over time.

The most significant changes to the model since our 2023 Outlook are:

- New formulations for carbon capture costs in power generation and hydrogen.
- New formulations for the cost of hydrogen from methane reforming with CCS.
- Improved and updated formulation for electricity and natural gas end-user price components.
- Incorporation of the new policy landscape, particularly the comprehensive US IRA package, renewable power support, hydrogen support, and CCS support.
- Updated formulation for nuclear, specifically the distinction between small modular reactors and large scale nuclear, and different technologies.
- Representation of biodiversity considerations in power investment costs.
- Representation of societal feedback on power project pipeline, success rate, and construction times.
- Adjustments to power sector investment costs, taking into account regional preferences for or against specific technologies due to energy security considerations.
- Representation of the effect of reshoring/onshoring on cost trajectories.
- Revised wind cost and technology parameters.
- Revised iron and steel demand, trade, efficiency, and energy demand.
- New formulations for methanol trade.
- Adjustments to power station investment logic.
- Improved storage cost formulas that better differentiate between energy storage and power cost components for long-duration storage.
- Improved cost modelling for net negative technologies and competition between BECCS and DAC.
- Updated the formulation for regional transmission and distribution grid demand.
- Updated historical data, including energy prices.

Modelling process and technical details
The ETO Model is built using the STELLA software, a platform specifically designed for system dynamics modelling. STELLA enables us to represent the energy system as a network of stocks (accumulations), flows (rates of change), converters (calculators of relationships), and connectors (causal links). This structure allows the model to effectively simulate complex interactions and feedback loops.

The model operates on a weekly calculation frequency for certain modules, such as the power market, which captures supply and demand imbalances on an hourly basis. However, the overall model runs on an annual time step, focusing on long-term trends rather than short-term fluctuations. The time horizon extends from 1980 to 2050, allowing for historical validation and forward-looking projections.

Energy demand
The ETO Model assesses energy demand through a detailed, multi-faceted approach that leverages system dynamics to capture the complex interactions between various drivers, including policy and behavioural influences. These influences manifest both explicitly, such as how increased recycling reduces demand for plastics, and implicitly, like the impact of anticipated electricity prices on the adoption of electric heating technologies.

The estimation process for sectoral energy demand follows a structured two-step method:

1. Calculation of Energy Services: We first determine the energy services required, such as passenger-kilometres in transportation, manufacturing output in tonnes, or heating demand for water heating. This step involves calculating the physical or economic output that drives energy consumption.

2. Forecasting Final Energy Demand: Using parameters related to energy efficiency and the dynamics of energy sources, the model forecasts final energy demand by sector and energy carrier. These calculations are underpinned by regional demand for energy services, which is modelled using non-linear econometric frameworks primarily driven by population growth and GDP per capita, along with other technological, economic, social, and environmental factors.

In the road transport sector, the ETO Model provides a detailed analysis of energy demand, focusing on vehicle-kilometres driven, vehicle sales, and the transition from internal combustion engines (ICE) to electric vehicles (EVs). The model projects vehicle demand by accounting for the saturation effects related to GDP growth in different regions, acknowledging that the number of vehicles per capita increases with economic development but at a declining rate as regions become more affluent. A key aspect of the road transport model is the EV uptake formulation, which is driven by a combination of cost and utility factors. The model employs a multinomial probit approach to simulate consumer choices between EVs and ICE vehicles, where the decision to purchase an EV is influenced by factors such as relative costs (including capital expenditure and operational costs), perceived utility (charging convenience, range, and environmental benefits), and network effects (such as the availability of charging infrastructure and the potential decline in ICE vehicle support services). The model dynamically adjusts the perceived utility of EVs over time as infrastructure improves and technology costs decrease, reflecting the evolution of the automotive market towards greater electrification.

For maritime transport, the model accounts for both cargo and non-cargo vessels, linking energy demand to the global production and consumption balance of energy and non-energy commodities. The energy use in this sector is influenced by factors such as the types of vessels, the distances covered, and the evolving mix of fuels, including the growing role of LNG and other alternative fuels. The rail sector is modelled with a focus on both passenger and freight services, where energy demand is driven by GDP growth, urbanization, and the expansion of rail networks. Aviation, being the most energy-intensive mode of transport, is modelled with particular attention to the impact of economic growth on passenger demand, the efficiency improvements in aircraft technology, and the potential shifts in fuel use towards biofuels and synthetic fuels. The model also considers the long-term effects of events like the COVID-19 pandemic on travel patterns and energy demand in aviation, reflecting the sector’s sensitivity to both economic conditions and technological advancements.

In the buildings sector, energy demand is estimated across residential and commercial buildings It considers five primary end uses: space heating, space cooling, water heating, cooking, and appliances and lighting. Key factors like building insulation, climate, and floor area are integrated into the model to determine regional space heating and cooling demand. Hot water demand is modelled based on living standards and population, while cooking energy needs are estimated considering household size and population metrics. The energy demand in commercial buildings is closely tied to GDP growth in the tertiary sector, which influences both floor area and the demand for energy services. The impact of data centres falls under the appliances demand of commercial buildings.

The manufacturing sector is a critical area of focus within the ETO Model. This reflects its substantial contribution to global energy consumption, particularly in energy-intensive industries like iron and steel, cement, and chemicals. The model estimates energy demand by first calculating the energy services required, such as the value added in USD across different subsectors, including base materials, manufactured goods, and construction activities. Energy consumption is then projected by considering specific industrial processes, such as process heating, machinery operation, and on-site vehicle usage, with a detailed breakdown for each subsector. Iron and steel production, for example, is modelled based on output measured in tonnes, with energy demand driven by downstream activities like construction and automotive manufacturing. The ETO Model also incorporates regional variations in production efficiencies, technology adoption, and shifts towards less energy-intensive processes. Additionally, the model dynamically adjusts the energy carrier mix, accounting for factors like levelized costs, carbon pricing, and policy incentives that influence the adoption of alternative energy sources such as electricity, hydrogen, and bioenergy.

Energy carriers

The ETO Model considers 12 energy carriers, of which seven are primary energy sources directly usable without conversion or transformation. These primary sources include:

- **Coal:** Includes both hard coal and brown coal, as well as derived fuels.
- **Oil:** Covers crude oil and refined products such as gasoline and diesel.
- **Natural Gas:** Encompasses methane, ethane, propane, butane, and biomethane.
- **Geothermal Energy:** Harvested from the Earth's crust.
- **Bioenergy:** Includes wood, charcoal, waste, biogases, and biofuels.
- **Solar Thermal Energy:** Captured via solar water heaters.
- **Off-Grid PV:** Electricity generated by solar panels not connected to the grid.

The remaining energy carriers are secondary forms derived from these primary sources: electricity, direct heat, ammonia, e-fuels, and hydrogen.

Energy transformations

The ETO Model manages power dispatch through a detailed simulation that operates on an hourly basis, reflecting the real-time balancing required between electricity supply and demand. The model considers 12 distinct types of power generation, from traditional fossil fuels to variable renewable energy sources like wind and solar. Each generation type is dispatched based on a merit order, which prioritizes the least-cost options to meet the current demand. The model accounts for the variability and intermittency of renewable energy sources by integrating them with storage technologies and flexible generation assets to ensure reliability. Additionally, load segments are categorized by their demand profiles and the dispatch is adjusted according to these segments to maintain equilibrium in the power market. This approach allows the model to simulate realistic hourly fluctuations in supply and demand, capturing the complexity of modern power systems.

> This dynamic investment framework ensures that the model not only reflects current market conditions but also adapts to potential future shifts in technology and policy offering robust projections for the evolution of power generation infrastructure over time.

When it comes to power investments, the ETO Model uses a profitability-driven algorithm to determine the addition of new generation capacity. The investment decisions are influenced by expected market prices, the levelized cost of electricity (LCOE) for each technology, and anticipated retirements of existing capacity. The model also factors in policy mechanisms such as renewable energy support schemes, carbon pricing, and the costs associated with CCS. Through a probabilistic approach, the model evaluates various scenarios to determine the most likely composition of new capacity additions, balancing the need for cost-effectiveness with the growing demand for energy. This dynamic investment framework ensures that the model not only reflects current market conditions but also adapts to potential future shifts in technology and policy, offering robust projections for the evolution of power generation infrastructure over time.

Hydrogen production is modelled with detailed consideration of various supply methods, including electrolysis and fossil fuel-based processes like steam methane reforming (SMR) and coal gasification. The model differentiates between hydrogen produced using grid electricity and hydrogen generated by off-grid, renewable-based electrolysers. The investment mix in hydrogen production capacity is determined by comparing the levelized costs of hydrogen from various technologies.

Extraction of fossil fuels

The supply of primary energy sources – oil, natural gas, and coal – is modelled with a focus on regional production dynamics driven by cost considerations. For oil, the model simulates production capacity as a globally competitive process across offshore, onshore conventional, and unconventional fields. The cost of transportation is factored into breakeven prices, influencing the future locations and methods of oil production.

For natural gas, the model assesses the portion of demand met by regional sources before determining new field developments based on resource limitations and breakeven prices. The model also integrates regional refinery capacities and capacities for gas liquefaction and LNG regasification.

Coal production distinguishes between hard coal and brown coal, with supply determined by regional mining capacity and geological availability.

Trade

Maritime transportation of energy carriers is a critical component of the ETO Model. For crude oil, the balance between regional production and refinery input determines whether a region exports or imports oil. Imports are primarily transported via seagoing vessels. For natural gas, shortfalls in regional production are supplemented by imports, with trade volumes adjusted based on existing trade shares and import cost projections. Similar assumptions apply to coal, where exports from coal-producing regions meet the demand of regions with domestic shortfalls.

The ETO models the trade of hydrogen, ammonia, and methanol by considering the production costs, regional supply-demand balances, and transportation costs. These energy carriers are traded based on competitive pricing, where exporting regions supply to those with a deficit, factoring in logistical constraints and the evolving infrastructure for global trade. The model dynamically adjusts trade flows by incorporating the development of new production facilities and the expansion of transportation networks, ensuring that the projections align with the growing demand for low-carbon fuels in a transitioning energy landscape.

The model also integrates the manufacturing sector into its trade module, linking the movement of non-energy commodities, including raw materials and manufactured goods, to global trade dynamics.

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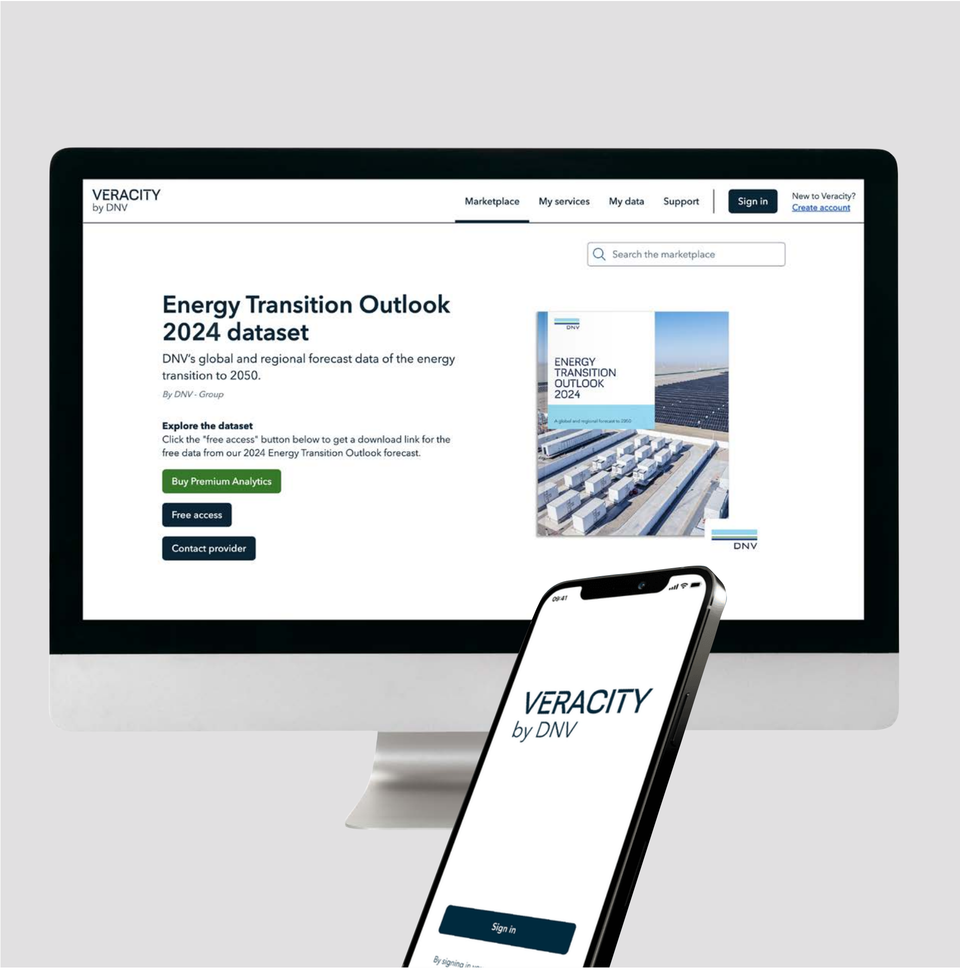

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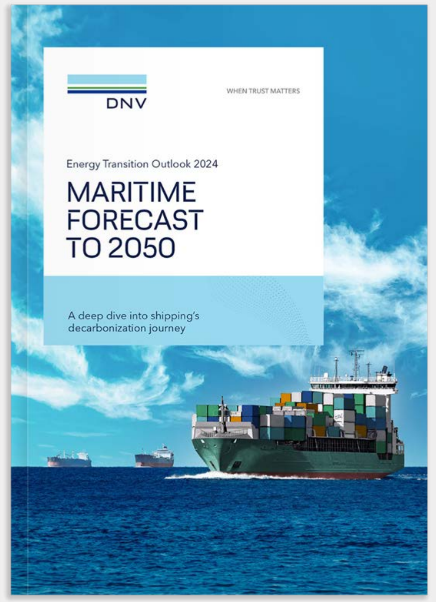
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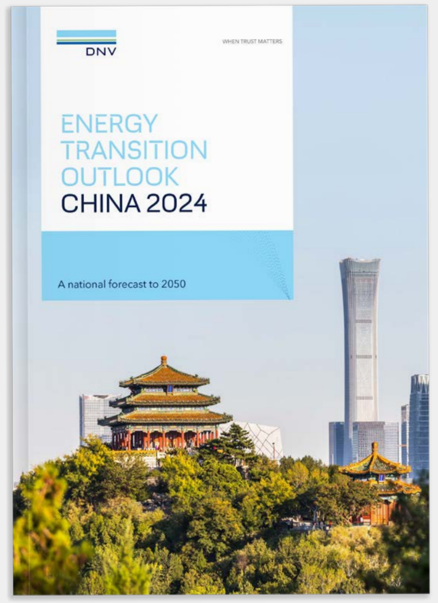
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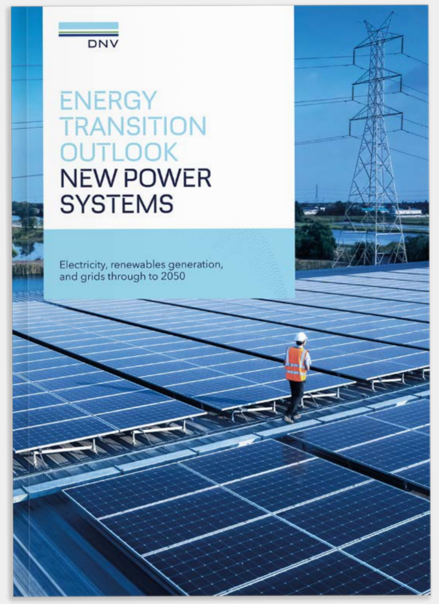
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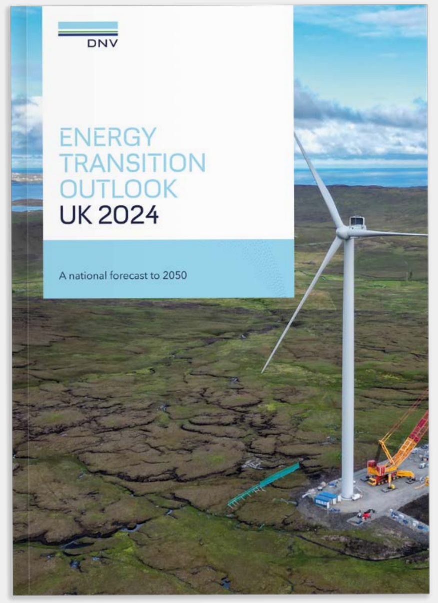
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Over the last year we have made adjustments to our model to enable the production of reports on the energy transition at country level. This year, we have released a UK Energy Transition Outlook, and ETOs on Norway and Spain to be released before the end of the year. Early in the new year, we will release a report on Germany's energy transition.

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THE PROJECT TEAM

This report has been prepared by DNV as a cross-disciplinary exercise between the DNV Group and our business areas of Energy Systems and Maritime across 20 countries. The core model development and research have been conducted by a dedicated team in our Energy Transition Outlook research unit, part of the Group Research & Development division. In addition, we have been assisted by internal and external experts, with the core names listed below:

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