DNV

WHEN TRUST MATTERS

PATHWAY TO NET-ZERO EMISSIONS

Energy Transition Outlook 2023

FOREWORD

Science tells us that we must achieve a net-zero energy system by 2050 to limit global warming to 1.5 degrees. With emissions at record levels and set to climb higher before peaking next year, the chances of hitting that target are now, admittedly, remote – but not impossible.

This *Pathway to Net-Zero Emissions* (PNZ) is effectively a blue-print for how that target can still be hit within the bounds of technical and political feasibility, and within the context of mainstream economic growth forecasts. However, our PNZ is also a blueprint for how to progress towards the target even though we may not quite reach it. Every tenth of a degree of warming counts, as the IPCC has outlined dramatically.

I use the word 'blueprint' advisedly. Our PNZ details how energy technologies work together in a pathway to net-zero emissions by mid-century. A blueprint is typically the starting point for project scheduling and also contains the details for requesting permits. We address those two issues in this report. Firstly, on scheduling, we show how time is of the essence – immediate, pragmatic action is required. Moreover, we find that almost all official net-zero ambitions that have been legislated, proclaimed, or included in policy documents need to be delivered roughly 10 years ahead of stated dates. Secondly, in our discussion of enabling policy, we show how tough choices, including bans and mandates, are unavoidable. We single out permitting of new infrastructure, including renewable sites and transmission and distribution grids, as the key bottleneck.

Our PNZ is not a 'burn now, pay later' scenario. The heavy lifting is done by accelerating the build-out of renewable sources and simultaneously cutting fossil sources. The numbers shown alongside this page bear this out. Most notable is the tripling of electricity production by 2050, with 21 times more electricity from solar PV and 15 times more from wind relative to today's levels. Coal exits the power system altogether, while oil and gas declines by some two thirds. There is considerably more carbon capture and removal but those technologies mainly deal with residual emissions from sectors and regions where decarbonization is exceptionally challenging.

Net-zero scenarios are often airily dismissed as 'unaffordable'. Our results show the opposite. While our PNZ entails a 5% uplift in energy expenditure relative to our 'most likely' energy future, we find that this still represents a smaller percentage of global GDP in 2050 than energy expenditure does today. That insight should stiffen the resolve of high-income regions to invest in a faster transition in low-income regions. And, for all decision makers, it throws into sharp relief the difference between a cleaner, more-efficient energy system and a world of mounting climate damage for generations to come.

Remi Eriksen

Group President and CEO

DNV

Comparing net zero with our present energy system

	UNIT	2022	PNZ in 2033	
Solar capacity (incl. off-grid)	GW	1 200	9 100	8 times more solar installed
Wind capacity (incl. off-grid)	GW	950	4 900	5 times more wind installed
Hydrogen (incl. derivatives)	Mt/yr	97	320	3 times more hydrogen
Share of EVs in passenger fleet	%	1.2%	26%	One fifth of the global vehicle fleet is EV
CO_2 captured through CCS	$MtCO_2$/yr	28	1 600	Capture capacity reaches 1.6 $GtCO_2$

	UNIT	2022	PNZ in 2050	
Oil demand	EJ/yr	176	59	Oil falls by two-thirds
Gas demand	EJ/yr	154	56	Gas falls almost as far as oil
Coal demand	EJ/yr	159	16	90% less coal
Grid-connected electricity	PWh/yr	29	80	Near-tripling of electricity production
Solar capacity (incl. off-grid)	GW	1 200	33 000	28 times more solar installed
Solar grid generation	PWh/yr	1.4	30	21 times more electricity from solar
Wind capacity (incl. off-grid)	GW	950	14 200	15 times more wind installed
Wind grid generation	PWh/yr	2	30	15 times more electricity from wind
Nuclear capacity	GW	390	1 100	Near-tripling of nuclear capacity
Hydrogen (incl. derivatives)	Mt/yr	97	760	Almost 8 times more hydrogen
Hydrogen share in final energy	%	0.01%	12%	
Share of EVs in passenger fleet	%	1.2%	83%	Transformation from current negligible levels
CO_2 captured through CCS	$MtCO_2$/yr	28	6 400	
CO_2 captured through DAC	$MtCO_2$/yr	0.01	1 600	

Fossil fuels Electricity Fast growers

HIGHLIGHTS

1.5°C is less likely than ever, staying as far below 2°C as possible is critical

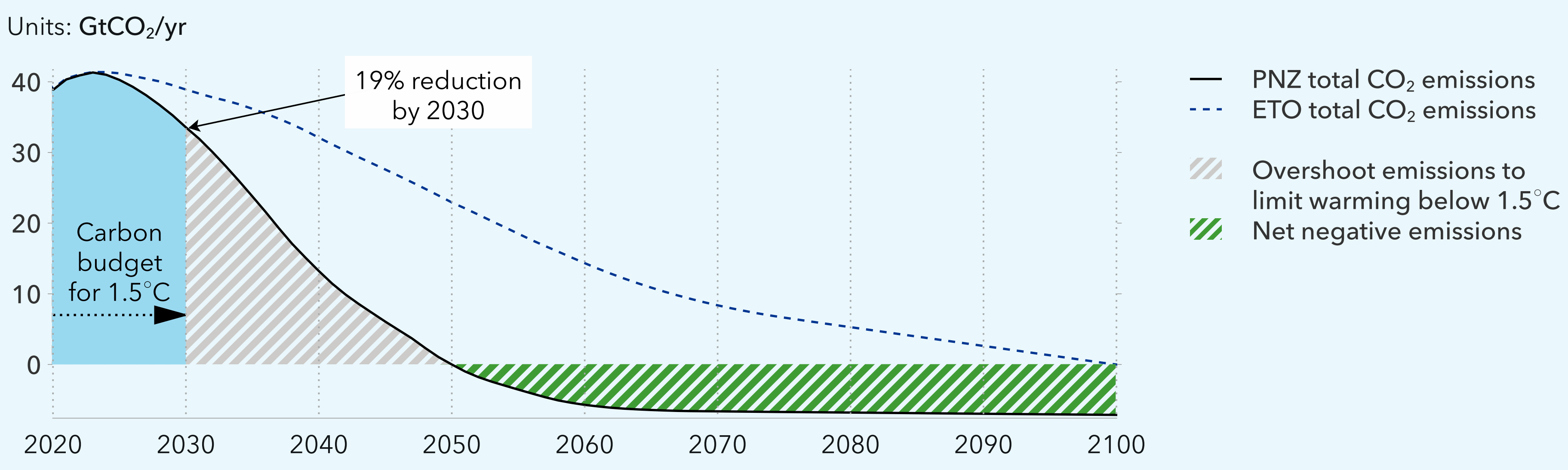
- A net-zero energy system by 2050 that secures a 1.5°C warming future remains a possibility, but its achievement is highly improbable
- CO_2 emissions are expected to reach record levels in 2023, but must decline by 19% already by 2030
- Given the present increase in emissions, all plausible net-zero pathways now factor in an 'overshoot' of emissions beyond 2050 that need to be tackled by net negative emissions technology. (DNV's pathway has an overshoot of 310 $GtCO_2$)
- Net-negative emissions at 6 Gt/yr between 2050 and 2100 to achieve 1.5°C poses a significant risk and depends on scaling of nascent technologies like direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS)
- Immediate, permanent cuts in fossil fuel use are necessary to keep the hope of reaching 1.5°C alive. Delayed action adds to the risk
- Every action to reduce emissions and accelerate transition is important, as it is crucial to stay as far below 2°C as possible

Some technologies are powering ahead, others must scale dramatically

- Solar PV and electric vehicles are scaling well, setting a pace close to a 1.5°C trajectory
- Most other technologies, including hydrogen production and carbon removal, are lagging behind the necessary scaling
- In the next decade, solar and wind capacity must together increase 5-fold, while storage capacity must grow 4-fold
- Energy efficiency improvements need to be double current levels
- Electricity must reach 47% of the energy mix in 2050, but that is dependent on rapid grid extensions which are already subject to critical permitting and supply chain bottlenecks
- Combustion of fossil fuels must fall by 78% to 2050, enabled by efficiency and fast replacement of oil, gas, and coal by renewable electricity, hydrogen, and biofuels. A massive carbon capture and removal effort, reaching 8 Gt in 2050, is essential to compensate for the remaining CO_2 emissions from fossil fuels

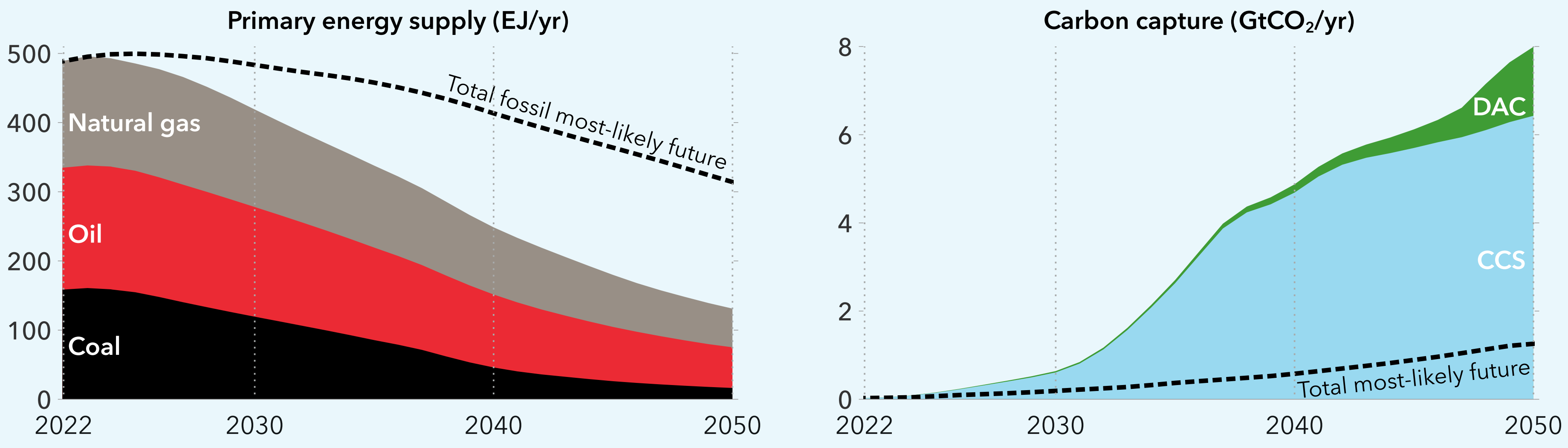
HIGHLIGHT 1

Pathway to net-zero emissions including overshoot and gap to be closed



HIGHLIGHT 2

The decline of fossil fuels and the rise of carbon capture



CCS: Carbon capture and storage; DAC: Direct air capture

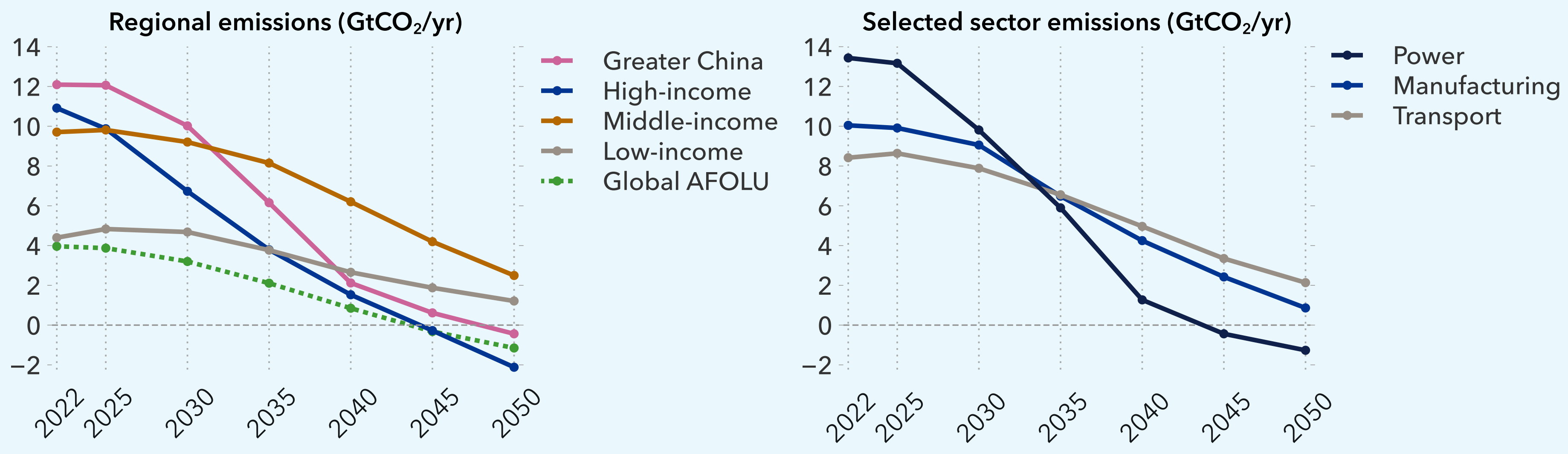
HIGHLIGHTS

All regions must decarbonize beyond present ambitions, but at different speeds

- To reach global net zero in 2050, high-income regions and leading demand sectors must move further and faster
- Acceleration must happen in a context where very few countries are on track to achieve even their present emission targets
- For global net zero in 2050, all regions must achieve their net-zero targets earlier than stated ambitions: OECD countries in the early/mid 2040s, China before 2050, and rest of the world before 2060
- Our PNZ is predicated on the UNFCCC's principle of common but differentiated responsibilities for net-zero. Regions decarbonize according to their capabilities, while balancing other SDG priorities. GDP per capita is a good proxy for the required pace of transition
- Sectors and industries will also decarbonize along differing timelines, with the power sector being a first mover reaching net zero in 2043

HIGHLIGHT 3

Regions and sectors move at different paces



AFOLU: Agriculture, Forestry, and Other Land Use

Policies must force deep decarbonization in all sectors

- Policy is the main lever for a faster transition, and all regions and sectors must accelerate
- There is an urgent need to rethink and establish new policies, with international cooperation ensuring ownership of actions across all countries
- High-income countries must finance infrastructure and decarbonization projects in low-income countries and de-risk investments
- Mandates and bans are unavoidable, especially for a drastic cut in fossil fuel consumption. No new coal, oil, or gas is needed; what exists in current fields is sufficient
- Behavioural shifts are needed for net zero, and some shifts must be mandated
- A sufficiently high cost on carbon is a necessity to discourage unabated fossil fuels

COP 28 is taking place in the context of global discord – and in a year that will set both new emissions and temperature records. Consensus may be difficult, but solutions for faster action are needed.

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1 INTRODUCTION

Despite the rapidly unfolding energy transition currently underway, DNV's *Energy Transition Outlook* (ETO) 2023 finds that the world is most likely headed towards 2.2°C global warming by 2100 relative to pre-industrial levels. Is it possible, then, to accelerate the pace of the transition to secure a warming future in line with the *Paris Agreement*? This report describes what DNV believes to be a plausible – but very challenging – pathway to achieve net-zero emissions (PNZ) by 2050 and a future where the global average temperature increase is limited to 1.5°C by the end of the century.

This pathway differs markedly from DNV's 'best estimate' forecast of the most likely energy future described in the 2023 edition of our ETO. Readers should note that in the report we use the term 'ETO forecast' to refer to the most likely future, in contrast to a PNZ future. Comparing our forecast with a pathway to net zero allows us to place a dimension on the scale of the change needed to achieve an energy transition that delivers a 1.5°C future.

We have set out to define, model, and describe a pathway that is technically and politically feasible, although we caution that our pathway tests the outer limits of political feasibility. Our PNZ relies on existing technologies and their scale-up, and not on uncertain scientific and technological break-throughs. It is politically feasible in that it relies on a proven toolbox of policy measures and allows for low-income regions to implement the necessary measures later than their high-income counterparts. All sectors will also not decarbonize at the same pace and with the same tools. To describe this 'tailored' transition, our report comprises several roadmaps for sectors and regions, detailing how each would contribute in our PNZ.

The ETO emissions forecast predicts 23 $GtCO_2$ of annual emission in 2050, showing there is a big gap to be closed to reach net-zero emissions by then. So, how to close that gap? Most of the CO_2 emissions can be avoided through implementing low-emission technologies in the energy system. There are technical solutions that need massive deployment and scale-up, such as renewable energy, storage, grids, hydrogen, and carbon capture. Other technologies must be scaled down, such as coal, oil, gas, and combustion engines. These actions alone will be insufficient, and there will also be a need to deploy significant amounts of carbon removal technologies. These could be nature-based solutions such as reducing deforestation and increasing sequestration in biomass. They could also be technical deployments like direct air capture.

Although we are confident that we have struck a realistic balance between viable technology and policy, the pathway we define is still an extremely challenging one, and there are undoubtedly alter-native routes to achieving a 1.5°C future. In its contribution to the IPCC's *Sixth Assessment Report (AR6) on climate change* (IPCC, 2022), Working Group III describes no less than 230 pathways that align with a 1.5°C future. Many other energy forecasters also regularly outline their vision of a net-zero pathway. Few, if any, model and describe a pathway to net zero as the sum of differentiated regional and sectoral transitions, as we do in this report.

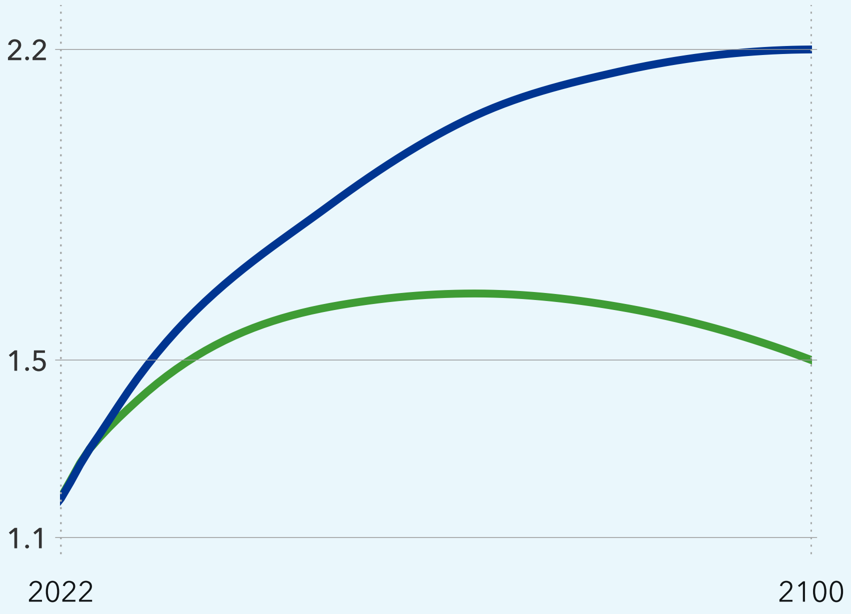
There might be some diverging views on assump-tions, technology choices, and adequate policies, but our PNZ and all these pathways point to the urgency and the scale of the action that are needed to curb the emissions at the necessary pace. Strong decisions must be taken now if we are to reach this target, and every delay makes the task more challenging.

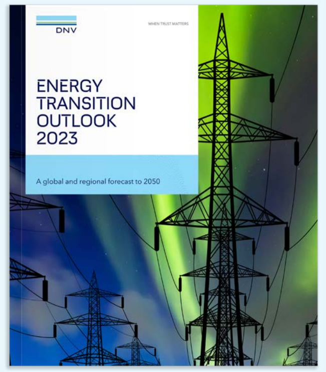
ETO and PNZ – forecast vs back-cast

FIGURE 1.1

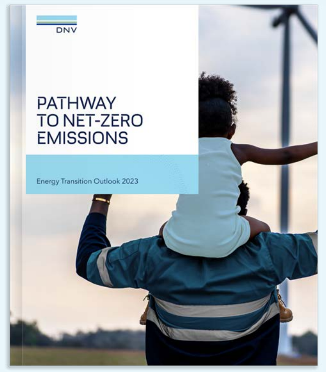
The focus of the ETO and the Pathway to Net Zero reports

Units: Change in average temperature with respect to pre-industrial levels (°C)





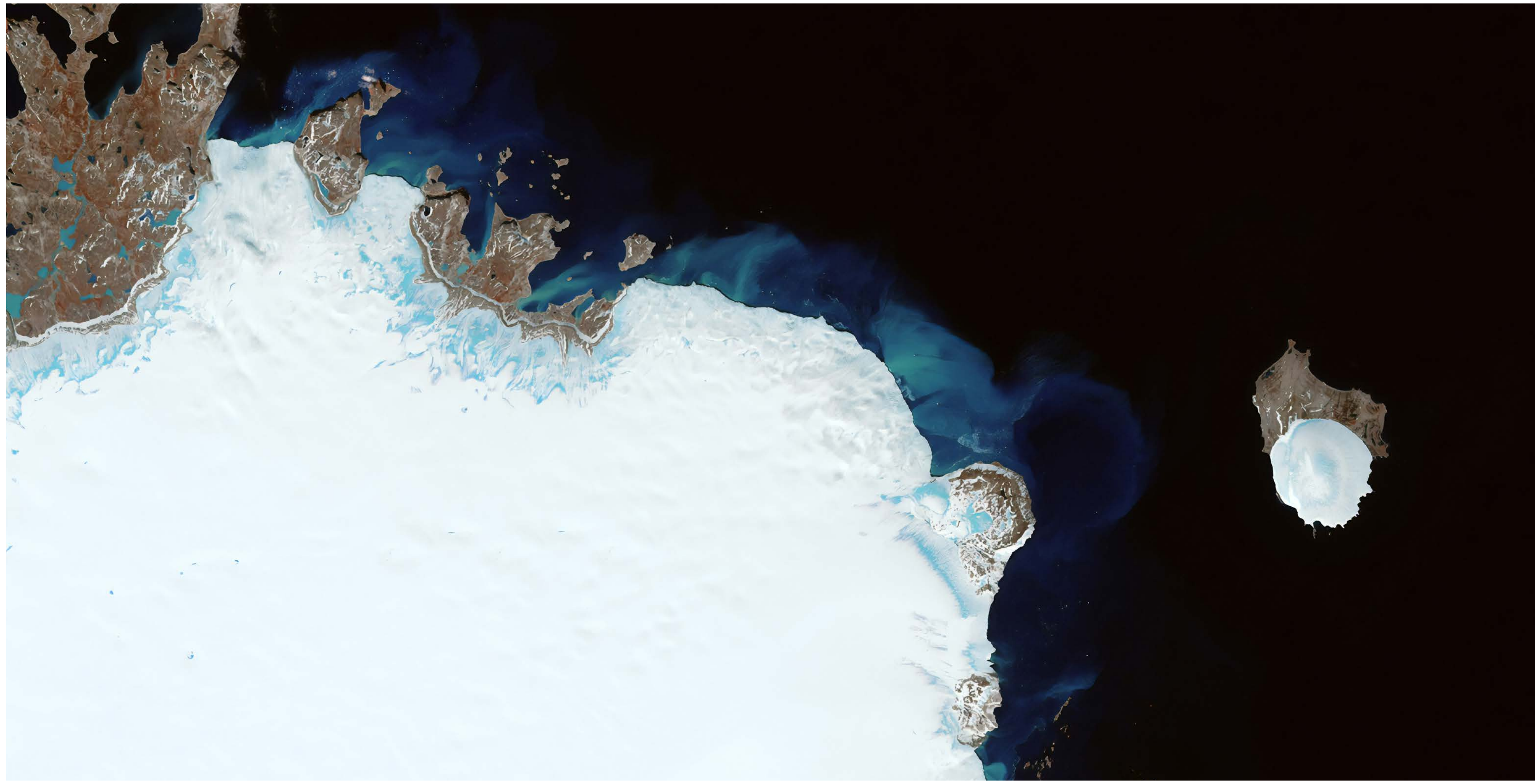
ETO 2023
Our 'most likely' energy transition forecast indicating warming of 2.2°C



PNZ 2023
A back-cast on how to close the gap to 1.5°C

1.1 IS NET ZERO REALISTIC?

Our annual ETO forecast (now in its 7th edition) describes the energy future that DNV considers 'most-likely' given expected economic, technology and policy developments. This is not a future in which energy- and process-related CO_2 emissions reach net zero in 2050 – far from it. It is logical to question, therefore, whether achieving a net-zero future by 2050 is at all realistic.



A 'most likely' future does not rule out other possible futures. In our view, net-zero CO_2 emissions by 2050 is still possible to achieve, but only barely. It will require urgent acceleration of targeted policies and simultaneous efforts from all regions and sectors. Considering that scale of effort, and record emissions at present, we caution that achieving net zero is less likely than ever. Nevertheless, this report outlines what we believe to be a possible, albeit very narrow, pathway to net-zero emissions. It includes detailed net-zero roadmaps for each major demand sector and each of the ten world regions covered in our analysis.

Achieving net zero by 2050 is realistic for some sectors, some regions, and certain countries; but that will not be sufficient to achieve global net zero. As some sectors and regions will *not* achieve net zero by 2050, others will have to go further and faster by strengthening their ambitions and achieving net zero before 2050 and net-negative emissions by 2050. Nations and sectors that conceivably can move faster will have to do so.

Individually and collectively, the sectoral roadmaps described in this report are all possible, but very tough. Nothing of this scale has ever been attempted. Their successful implementation will require not only strong contributions from technology and finance, but an extraordinary step-up in energy, climate, industrial, and economic policies along with behavioural changes. Moreover, these changes and emission reductions must happen simultaneously. Alternatively, if some sectors or regions underperform in relation to the decarbonization roadmaps, other sectors or regions will have to frontload their transformations to over-deliver on already-challenging roadmaps. Each of the roadmaps we set out here is challenging; the probability of all being realized is low. If by 'realistic' we mean a clear or better-than-even chance of achieving something, then we would need to concede that net-zero CO_2 emissions by 2050 is unrealistic. However, it is *possible* and, given what is at stake, it is imperative we do our utmost to achieve it.

Ultimately, at some point in the future, humanity is likely to hit net-zero emissions because the alternative is untenable – i.e. average global temperatures will simply keep rising. The question therefore is not if net zero, but when? From where we are now, where CO_2 emissions have not yet peaked, that 'when' seems very unlikely to be 2050. However, every tenth of a degree of global warming matters disproportionately. Climate change is here already, driven by cumulative emissions that have already forced a temperature increase just beyond 1°C above pre-industrial levels. The impact is visible to all, with devastating societal implications and rising economic losses felt world-wide. From this point on, even relatively small additional increases in temperature give additional long-term consequences and risk triggering planetary tipping points. Because risks and impacts pile up extraordinarily for warming above 1.5°C, the rational response is surely to expend extraordinary effort now and in the coming years to prevent a very dangerous future.

DNV's contribution lies precisely in not painting a rose-tinted view that net-zero emissions is easy to achieve. Instead, we provide a reality check on how difficult the goal really is. Is net zero probable? No. Is it irresponsible therefore to still talk about it? Absolutely not. Science has dictated a target and the rational response is to try to come as close to it as possible.

1.2 WHERE IS THE ACTION FOR NET ZERO?

For many decades, scientists have warned about the risk of climate change and pointed out the necessary measures to prevent its escalation. Near consensus among scientists, as summarized in IPCC's *Assessment* reports and the annual COP meetings, is raising an increasingly bigger red flag. United Nations Secretary-General António Guterres' warning of "Code Red for humanity" leaves no doubt as to where we are headed. The *Climate Change 2023: Synthesis Report* (IPCC, 2023) has never been clearer in its language and message: "Climate change is a threat to human well-being and planetary health (very high confidence). There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all (very high confidence)".

Judging from the ambitions announced by politicians and the deep concerns voiced by the general public, the warnings seem to be heard. But those ambitions are not translating into programmatic action for net zero, with very few exceptions. At a time when the IPCC is calling for at least a sixfold increase in finance provided to emissions reductions projects by 2030, the Climate Tracker world map (https://climateactiontracker.org/) is still devoid of the colour green denoting a country that is '1.5°C Paris compatible'.

What explains the lack of progress?

There are opposing forces and many barriers to the energy transition, as we have discussed in our ETO publications (DNV, 2022; DNV, 2023). These include, in no particular order, fossil-fuel subsidies, resistance from vested interests, corruption, short-term priorities, unfit regulatory frameworks, lack of global cooperation, energy system inertia, corporate greenwashing, policy reversals, and so on. While these barriers collectively are not sufficient to prevent an energy transition from happening, they are certainly hindering a fast transition. Some of these barriers are unnecessary and should be removed; other barriers are more systemically difficult to address.

Emissions reduction is one of many priorities that nations face. The 17 Sustainable Development Goals, with climate action as the 13th goal, clearly pinpoint multiple, urgent global priorities. Yet, research – e.g. DNV's *Future of Spaceship Earth* report (DNV, 2016) – finds that climate action is a prerequisite for meeting many, if not all, of the other SDGs. Recently, a UN status report emphasized that climate-related disasters are in fact already hindering progress towards the SDGs (UNECOSOC, 2023).

There are obvious synergies between priorities such as climate action (SDG 13), affordable and clean energy (SDG 7), and ensuring good health and well-being (SDG 3), for example reduced air pollution in cities that favour clean electricity over coal. Other goals are in conflict with climate action, e.g. replacing traditional biomass used for cooking with natural gas to avoid indoor air pollution, or protecting nature (SDG 14 and SDG 15) by not allowing acreage for new renewable energy build-out.

While climate action should always be top of mind, it should not always have priority; holistic planning and policymaking is needed to carefully manage dilemmas. Yet further complicating policymaking are the 'twin tragedies'. The first of these is the tragedy of the commons, where the common restraint on emissions required to protect the physics of our common atmosphere is undermined by countries and other actors seeking to maximize short-term gains through emissions-intensive activities. That is related to 'the tragedy of horizons', a term coined by Mark Carney, former governor of the Bank of England, to describe the catastrophic impact that climate change will have on future generations while noting that the current generation has little incentive to fix it (Carney, 2015).

We should add that there is also a tragic lack of comprehension among the many who dismiss a net-zero energy system as impossibly disruptive and expensive. We show in this report that net zero is not only achievable with the technology that exists today, but it delivers, in short order, an efficient and clean energy system that would see the world spending considerably less on energy as a proportion of GDP than it does today. We acknowledge that our pathway to net zero does not solve all related challenges, including the biodiversity crisis and the challenges associated with non-energy-related SDGs, including a just transition. But our pathway will, at the very least, reduce the risks of climate change that threaten to derail all other goals.

Net zero is a race to a cleaner, more efficient energy system that costs less as a percentage of GDP

2 A NET-ZERO POLICY

Reaching the 1.5°C goal is first and foremost a political decision. The scale of change needed requires action across many policy areas and co-ordination across many systems, as outlined in this report. This can appear daunting, but there is growing evidence that climate action need not come at the expense of development and poverty reduction – especially where the focus is on inclusive development to reduce people's vulnerability to climate change.

Current 2030 climate targets are not met in our ETO forecast of the most-likely energy future, let alone sufficient for a net-zero pathway. Recalibrating policy for net zero requires strong political will, international collaboration, and public engagement to maintain public support. Research has shown that this is best achieved through mission-oriented innovation approaches to better co-ordinate policy areas and administrative silos (Larrue, 2022). There is a risk, however, that the mission itself can over-emphasize science, technology, and innovation (STI) at the expense of broader social gains. Creating a shared, public sense of mission is best achieved by building consensus around the positive aspects of climate action – the health benefits of clean air, the preservation of forests and mangroves as natural flood defenses, the productivity-boosting benefits of clean electricity, and money saving end-use equipment like heat pumps (Hallegate, 2022).

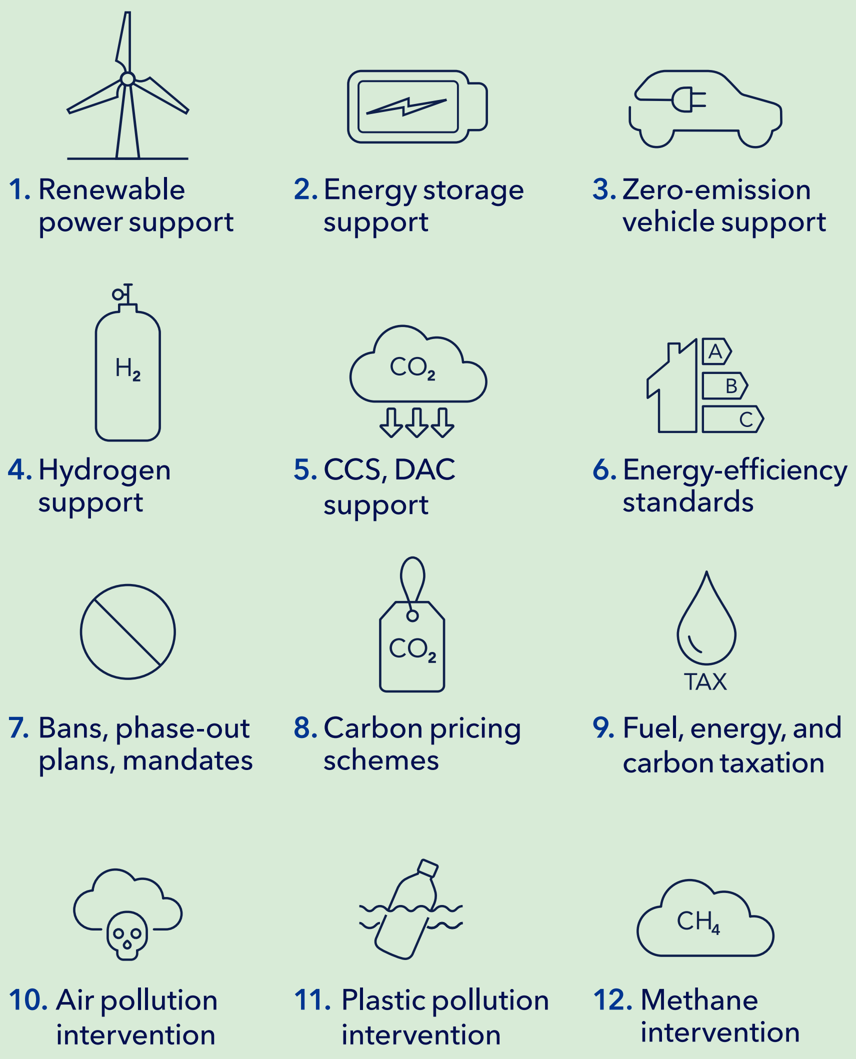
Bending the emissions curve requires credibility in terms of commitments and delivery plans. The cost of capital is driven by risk perception. When long-term stringent policy paths are priced into the financial markets, this will lead to higher cost of capital for carbon-intensive investments.

Time is of the essence in the transformation of economies and the sectors within them, and only through a combination of mandates, requirements, incentives, disincentives such as carbon pricing, and continued R&D, can decarbonization solutions be developed and deployed at scale and speed across sectors and regions.

DNV's PNZ activates the entire policy toolbox and intensifies policy factors to shift the supply mix and deploy decarbonization options amongst end-use sectors (Figure 2.1). Our pathway relies on a mix of policy instruments, combining direct regulation with requirements and limits on pollution (i.e. emissions), phase-in and phase-out policies, technology-specific support, and economic instruments – 'sticks and carrots' – to bring emissions as close as possible to zero. Our pathway then relies on carbon removal technologies both for any remaining emissions and to compensate for carbon budget overshoot emissions.

FIGURE 2.1

Policy factors triggering the pathway



Government spending and finance must be net-zero aligned

A redirection of public investment towards infrastructure and clean energy projects must be matched by streamlining and fast-tracking permitting regulations. In addition, administrative procedures to access government support need simplification. Supply-side and demand-side support are needed to advance technological change at scale and stimulate markets for net-zero aligned products and behaviour.

For a speedier transition in middle- and low-income regions, there is a need for collaboration and concessional (below market rate) finance and grants that de-risk investments in capital intensive renewables. Funding needs to flow as outlined by the Independent High-Level Expert Group on Climate Finance (Songwe et al., 2022) at the request of the Egyptian and UK Presidencies of COP 27 and COP 26, which concluded that USD 1trn/year, beyond the earlier promised USD 100bn/year, is the external finance needed in developing countries (other than China) by 2030 to deliver the *Paris Agreement*. Examples of existing decarbonization investment include the Just Energy Transition Partnerships, the G7 Partnership for Global Infrastructure and Investment (PGII), and the greening of China's Belt and Road Initiative. Financing at this level needs to be accompanied by multilateral consensus-building around risk and opportunity: that for low-income countries risk does not lie in being denied access to polluting technologies but rather in not being able to access more efficient cleantech that unlocks productivity and draws those countries into low-carbon value chains as valued trading partners (Hallegate, 2022).

Fossil-fuel subsidies, reported by the International Monetary Fund (Black et. al, 2023) at a record level of USD 7trn in 2022, need to be scaled back.

Financial regulation needs to unlock net-zero investment practices by ensuring transparent disclosure of climate-related risks such as the US Securities and Exchange Commission (SEC)'s Climate Disclosure Rule (proposal) and EU's *Sustainable Finance Disclosure Regulation*. Green taxonomies prompt private financial institutions' capital allocations aligned with net zero, such as in the EU and ASEAN 's Taxonomies and the People's Bank of China's Green Bond Endorsed Project Catalogue.

Stringent net-zero policy must address public acceptability

When designing climate policy interventions, politicians need to read the public and their economic circumstances with empathy (Marshall, 2023). Public engagement, a society-wide dialogue and sense of collective effort are essential for policy success. Interventions that hit people's pockets, such as fossil-fuel taxation and subsidy reforms, risk public backlash in high-income and low-income regions alike. Examples are plentiful: the 'yellow vests' protests in France against fuel-tax increases, protests in Kazakhstan against lifting price caps (Horowitz, 2022), riots in Nigeria over attempts to abolish fuel subsidies (Layade-Kowo, 2023), and in Kenya where a fuel subsidy was reinstated to stabilize retail fuel prices in response to public anger over higher cost of living (Reuters, 2023). Where trust in government is already low, subsidy removal without providing incentives and clearly publicizing the benefits of moving to cleaner technology is a spark for conflict.

Studies show that people are willing to contribute to a net-zero transition (Whitmarsh et al., 2023), especially when the effectiveness and upside of climate policies are emphasized. Convenience and affordability are key issues influencing behavioural change and require both regulation and incentives. Win-win measures, such as home insulation, that cuts both energy bills and emissions, stand a better chance. Research has shown that by shielding manufacturing facilities from the effects of fuel-price hikes, fossil-fuel subsidies have the perverse effect of disincentivizing investment in much more efficient electrification (Cali et al., 2022); the implied opportunity cost should be demonstrated and widely communicated. Socio-economic effects on workers and entire communities need to be managed through domestic and regional measures (e.g. the EU's Just Transition Mechanism) and international collaboration.

Sectors and regions to move at different speeds

At the level of sectors or supply chains comprising several decarbonization solutions, a blend of policy measures must be implemented. Sectoral policies forging the PNZ are presented in Chapter 4. Net-zero policy levers in the ten global regions are detailed in Chapter 5 and these recognize that regions have varying levels of responsibility and capabilities. DNV's PNZ imposes a greater burden on the regions that are better placed economically and with competence for immediate clean technology deployment, and to progress the technical readiness in key abatement technologies that need to be validated at commercial scale to enable net zero.

Carbon pricing must disincentivize emissions

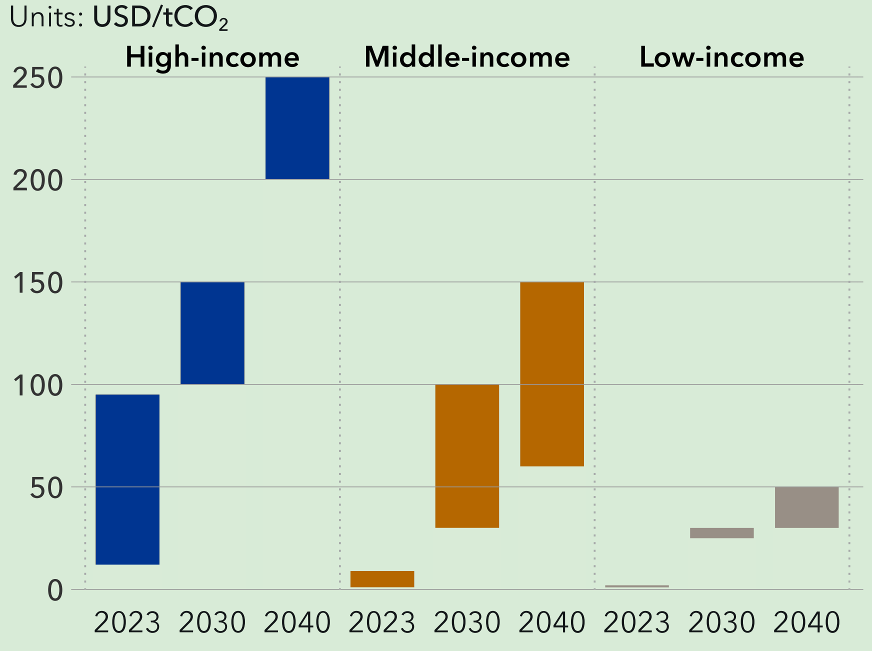
Carbon pricing is essential to disincentivize emissions and divert direct spending and investment out of emission-intensive alternatives. It is also a central instrument to fund net-zero spending. Political trust in how fees will be used influences support for CO_2 and environmental taxes. Acceptability can also be enhanced through carefully designed recycling mechanisms to handle distributional fairness and household impacts (Kleinert et al., 2018; Fairbrother et al., 2023).

The flagship report from the High-Level Commission on carbon prices specified that "prices would need to be in the USD 50 to USD 100/tCO_2-e range by 2030, provided a supportive policy environment is in place" (CPLC, 2017). The International Monetary Fund proposed international carbon price floors to reinforce the Paris Agreement but with consideration for economic development (Parry et al., 2021; Chateau et al., 2022). Differentiated price levels for high-, middle-, and low-income countries, respectively were suggested with resultant burden-sharing shifting economic cost of mitigation to high-income regions.

To achieve DNV's pathway, carbon pricing is not the only policy measure but forms part of supportive policy packages. Prices are cognizant of regions' economic circumstances. Our differentiated carbon price levels in high-, middle- and low-income regions are shown in Figure 2.2. Europe, North America, OECD Pacific, slightly above Greater China, reach carbon price levels of USD 100–150/tCO_2 in 2030 and USD 150-250/tCO_2 in 2040. By 2050, regional trajectories range from USD 50 to 250/tCO_2.

FIGURE 2.2

Carbon price by region



Boxes show regional spreads. See Chapter 5 for details on regions.

3 THE PATHWAY

We designed our pathway to net-zero emissions (PNZ) so that global CO_2 emissions in 2050 hit net zero. The present annual (2022) emissions are 41 $GtCO_2$ and our ETO forecasts 2050 emissions of 23 $GtCO_2$. If we are to close this gap and limit the global average temperature increase to 1.5°C, it will be through very tightened energy, industrial, and climate policies in all regions and sectors, and by applying the entire policy toolbox.

The pathway we describe, and the forceful actions it requires, leads into uncharted territory on a global scale, and its low likelihood means we must define the key assumptions in our model. The key constraint is time. While our pathway is one of many, the world must not wait for consensus on a plan.

There is, however, clear consensus on the urgency of the action needed to stay below 1.5°C, and general understanding of the overarching requirements. CO_2 emissions will mostly be cut by implementing low-emission technologies in the energy system. Massive deployment and scale-up is needed in renewable energy, storage, grids, hydrogen, and carbon capture and storage (CCS), among others. There must be big cuts in the use of coal, oil, gas, and combustion engines. Behavioural change (e.g. reducing air travel) is also essential to rapidly curb emissions.

The key constraint is time: the world must not wait for consensus on a plan.

Need for carbon removal

In our PNZ, the carbon budget for staying below 1.5°C is exhausted by 2030, and there is a need to deploy significant amounts of carbon-removal technologies. These could be nature-based solutions such as reducing deforestation and increasing carbon sequestration in biomass. They could also be technical deployments like direct air capture (DAC). Cumulative removal of CO_2 must reach almost 7 $GtCO_2$ per year by the end of the century to remove the overshoot accumulated by 2050, and compensate residual fossil-fuel emissions.

Gross zero and net zero

While net-zero emissions is a logical goal on a global scale, it should be applied with care at regional and sectoral scales. There is a big difference between net zero and gross zero, and a global net-zero future does not mean all sectors and regions will meet the zero-emission target by 2050. It is both implausible and unjust to expect a gross-zero result in which all sectors, regions, and countries achieve this challenging goal simultaneously.

Each region differs in its emissions status and ability to reduce emissions. Similarly, the readily available abatement options vary considerably between demand sectors.

Accordingly, our pathway applies the net-zero approach on only a global scale, while allowing for a large differentiation on a regional scale. Similarly, we apply the net-zero approach to the entirety of energy demand rather than individual demand sectors, which decarbonize at different rates.

A fair transition

While the concept of a 'just transition' is compelling, we have not attempted to model a dramatic transfer of wealth across world regions over the next 30 years. This choice is partly because energy provision and consumption is a relatively small component of total economic activity, and because such wealth transfer is not very likely to happen anytime soon. Therefore, in our PNZ we have applied the same population and GDP growth assumptions – and consequently the same GDP per capita in 2050 – as we use in our ETO forecast of the 'most likely' energy future. While this is inconsistent with the notion of a just transition, a greater injustice would arise from the expectation that all regions should move at the same decarbonization pace regardless of their different starting positions.

We have therefore scaled the implementation of mitigation measures to achieve net zero relative to the GDP per capita of the region. Arguably, our approach thus balances the fair and the plausible.

3.1 THE TRANSFORMATION OF THE ENERGY SYSTEM

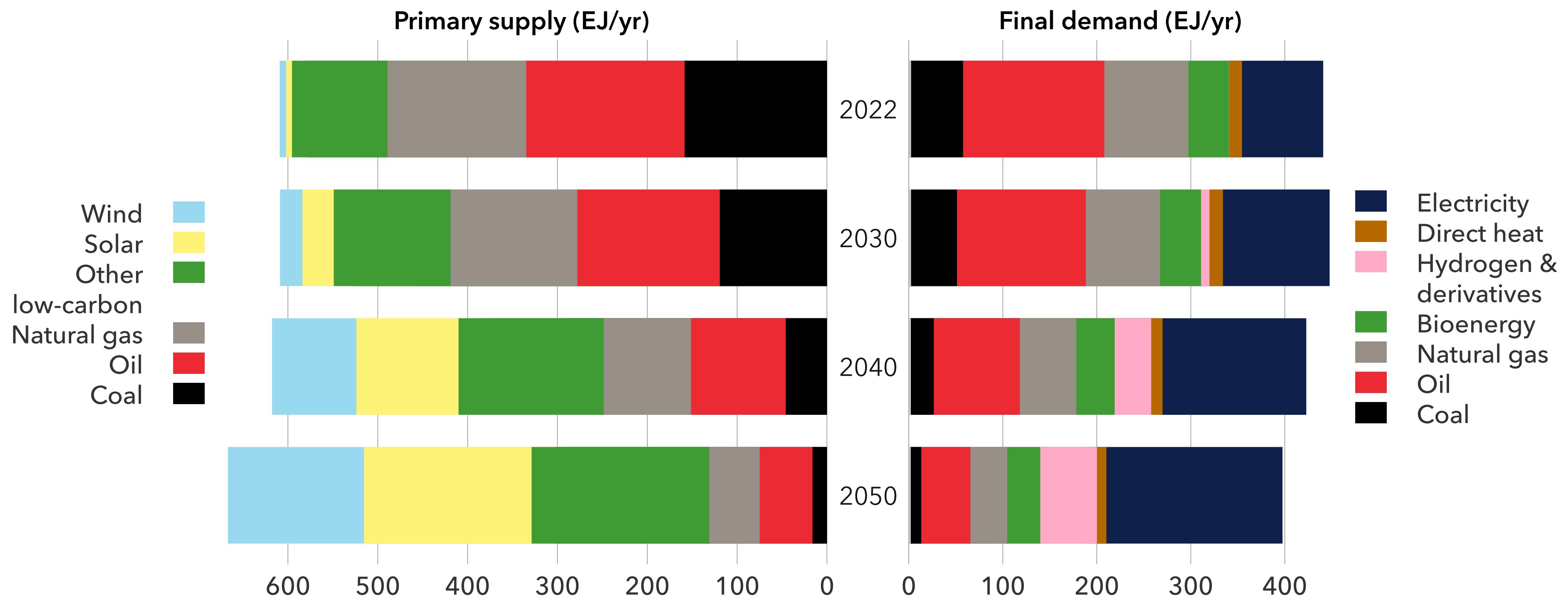
The decoupling of economic activity and energy use must intensify under the PNZ. A massive ramping up of variable renewable energy sources (VRES), accompanied by a drastic near phase-out of coal and strong decline in using the other fossil fuels, is equally fundamental to achieving our PNZ.

Final energy demand in the PNZ is 398 EJ in 2050, 10% less than in 2022. The declining energy use does not mean we would have fewer energy services. On the contrary, the PNZ effectively leverages the benefits of energy efficiency and electrification.

The primary energy supply mix in 2050 in the PNZ is very different from today, with fossil fuels retaining only a 20% share versus 80% now. This contrasts with our ETO estimate of an almost equal share of fossil and non-fossil energy sources by mid-century. Additionally, our assumptions regarding population and GDP are identical in both cases, clearly indicating that the PNZ is an energy-efficient pathway with a higher share of more efficient renewable energy helping to deliver the required level of decarbonization together with carbon capture and removal.

FIGURE 3.1

World primary energy supply and final energy demand



Fossil fuels

- Coal is nearly phased out in our PNZ but is still used mainly for manufacturing in regions such as Greater China and the Indian Subcontinent, whose transitions lag the developed regions, with a later phase-out of coal.
- Despite the push to eliminate unabated fossil fuels completely, oil still persists in the energy system in 2050. This is due to its prevalence in hard-to-abate sectors such as aviation and continued but limited oil use in the road sector in developing countries where charging infrastructure is not fully built out by 2050.
- The PNZ also has natural gas in the mix in 2050, but most of its use is coupled with CCS or similar abatement technologies.
- Both oil and gas also retain a fair amount of residual use in the non-energy sector, for example as feedstock for plastics, but this fossil-fuel use is not causing any direct emissions.
- CCS is essential to abate the remaining emissions where possible. About 2.1 $GtCO_2$ from fossil fuels are captured by 2050, covering a third of the fossil-fuel emissions.

Low-carbon technologies

- Solar and wind together provide more than half of primary energy supply in our PNZ. With continued high learning rates, there is positive reinforcement at work in installing more and more solar and wind, which continues to bring down the levelized costs of these energy sources. The share of solar and wind in 2050 is almost double that of their share in our ETO.
- Bioenergy increases its share and role in our PNZ, growing from 10% today to 15% in 2050. This is due to multiple factors: heat-only plants having to use bioenergy; greater bioenergy use in manufacturing; and bioenergy use for producing biofuels, especially for aviation and maritime sectors. Regulations and mandates aim to replace natural gas with emission-friendly biomethane where possible and available.
- Because of its stable and dispatchable electricity and its long lifetime, hydropower still plays a role in the net-zero energy mix. Its share increases slightly from 3% today to 4% by 2050.
- Spurred by energy security concerns, the share of nuclear power more than doubles from 4% in 2022 to 10% in 2050 despite the fierce competition of solar and wind power.

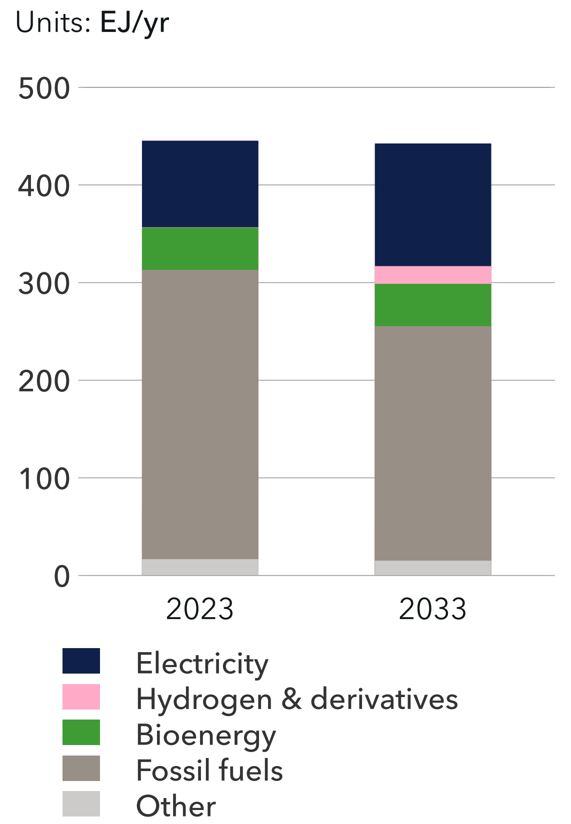
A CLEAR PATHWAY FOR THE NEXT DECADE

The massive transformation in the energy system in our PNZ starts strongly in the coming decade, building the foundation for the rest of the transition

Massive electrification effort in final energy demand

- 19%
Fossil fuels

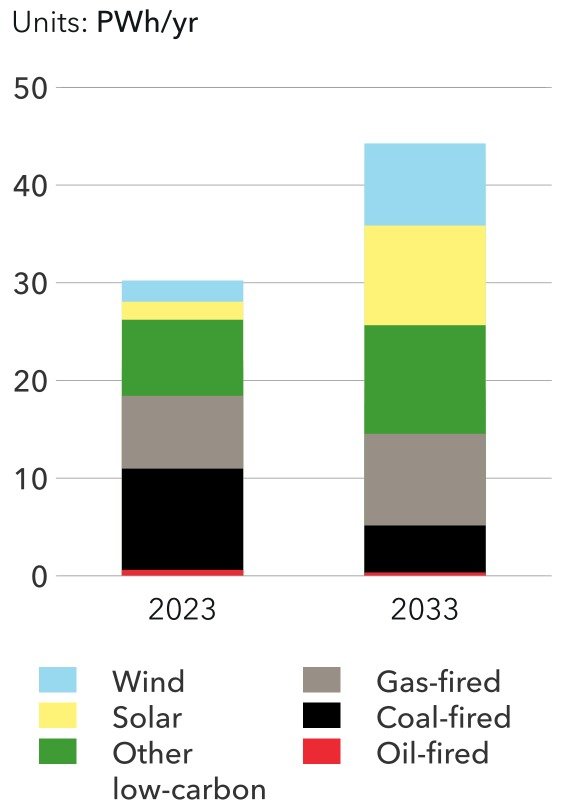
+ 42%
Electricity



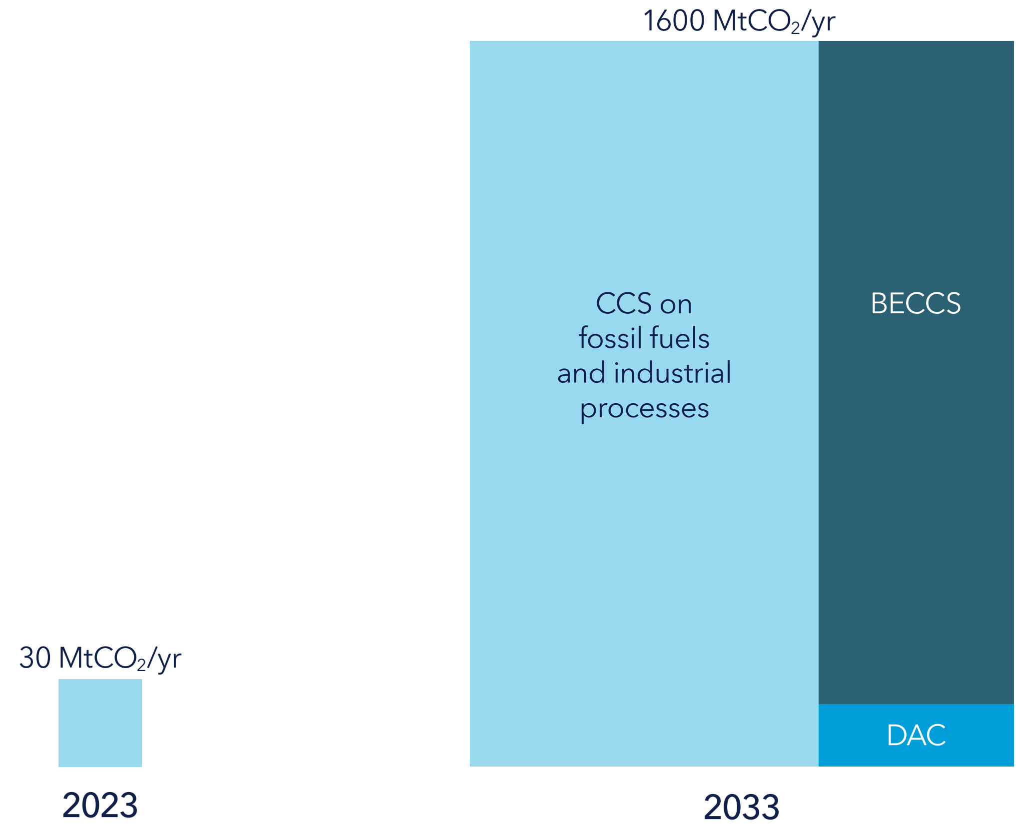
Increased and greener electricity generation

+ 7,200 GW
Solar and wind capacity

50%
Reduction of coal-fired generation



The rise of carbon capture and removal



	Average wind capacity addition	Average solar capacity addition	Oil production	Grid and renewables expenditures	Battery capacity
The last decade (2013-2023)	+ 37% p.a.	+ 43% p.a.	+ 1% p.a.	+ 3% p.a.	+ 61% p.a.
The next decade (2023-2033)	+ 16% p.a.	+ 16% p.a.	- 2% p.a. (No new oil)	+ 8% p.a.	+ 47% p.a.

3.2 FOSSIL FUELS

PNZ	Share in primary energy	80% in 2022	20% in 2050
PNZ	Share in electricity production	61% in 2022	8% in 2050

The unavoidable decline and voyage into the unknown
Fossil fuels have dominated the energy system for more than a century. They are the main source of anthropogenic CO_2 emissions and their phase-out is unavoidable to reach a decarbonized energy system. The system has a lot of inertia, but fossil fuels, which account for around 80% of primary energy supply today, will see their share decline to 20% in less than 30 years in our PNZ.

This fast decrease would have consequences that are hard to foresee. Oil and gas production has steadily increased in the past decades, and a declining demand is uncharted territory. It should be emphasized that the regional spread of production is uncertain. This is because supply-side policies to control production in an oversupplied, shrinking market have yet to be agreed upon by hydrocarbon producing countries; this is unknown and unfamiliar territory for the oil and gas industry. The consequences for production quotas and market prices are therefore highly speculative.

For oil and gas, our assumption is that regions with lower production costs and less stringent climate policies (i.e. Middle East and North Africa and North East Eurasia) would gain increasing shares in production. For coal, production would still mostly meet domestic demand, with Greater China and the Indian Subcontinent accounting for about two-thirds of the remaining global production.

Carbon capture is essential to abate remaining fossil emissions
Without CCS, reaching net zero will be virtually impossible. It is a convenient solution to abate fossil-fuel emissions in existing installations (in power production or in manufacturing) that cannot realistically be replaced by low or zero-carbon alternatives on a short timescale. CCS-based solutions can also be more competitive, especially in the short term.

CCS facilities have operated for several decades in areas such as enhanced oil recovery or fertilizer production where the CO_2 can be captured at a relatively low cost. However, for as long as there are fossil fuels in the energy mix and emissions from production processes, CCS will be sorely needed.

Energy use from coal and oil falls rapidly in our PNZ, while gas shows a more moderate decline. Additionally, capture rates are higher for coal and gas, where much of the CO_2 is emitted at large point-sources, compared with oil which typically has many small point-sources. That is why most of the captured emissions are from natural gas and coal.

As a result, our PNZ sees coal emissions reducing by 97%, gas emissions by 85%, and oil emissions by 76% to mid-century, despite continued use.

FIGURE 3.2
World primary fossil-fuel supply by source

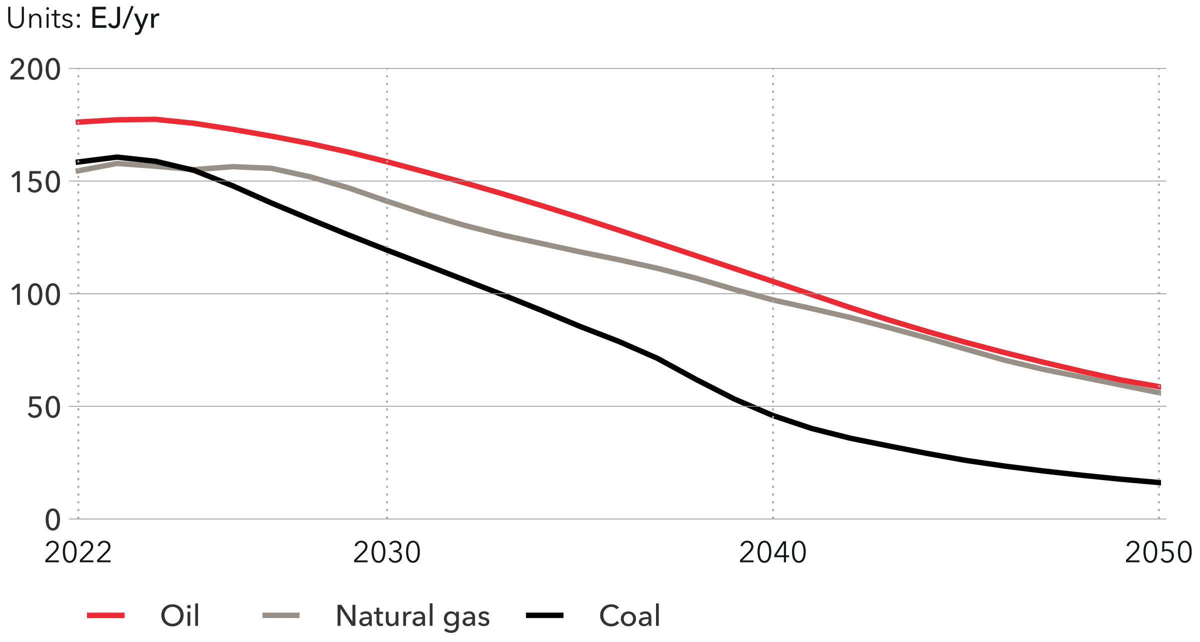
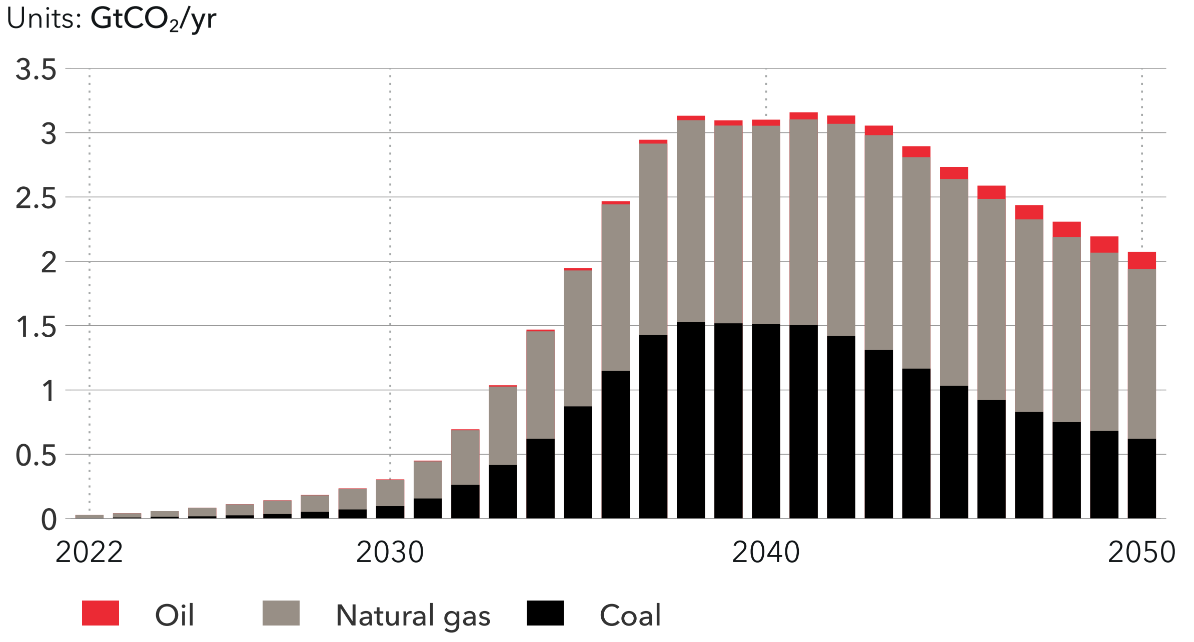


FIGURE 3.3
Fossil-fuel captured emissions



Coal

Due to its high emission intensity, coal is the first target of decarbonization policies. The power sector sees a complete global phase-out of coal in electricity production by 2050. While coal use in power generation has alternatives that are competitive today and will increasingly be so in the future, there are other sectors that are costly to abate. For high-heat processes, coal's phase-out will therefore be slow. In the PNZ, 800 million tonnes of coal would still have to be extracted in 2050, exclusively as hard coal used almost solely in industry.

Oil

After the 2021-2022 rebound from the COVID-19 pandemic, global oil demand in the PNZ rapidly declines by two thirds to 59 EJ per year in 2050. The lion's share of this remaining demand is split between the non-energy sector (34%), where oil would continue to be used as a feedstock for producing petrochemicals and plastics with no major associated emissions, and in the transport sector (49%). Within transport, the remaining demand is concentrated in the road sector in lower-income regions (81% of total) and in the hard-to-electrify aviation sector (18% of total). Nevertheless, overall transport demand for oil will fall 74% by 2050. Non-energy demand declines only slightly, as oil is nearly impossible to replace in the sector. A small share of oil demand by 2050 is in manufacturing, within subsectors such as construction, mining, and cement. The two regions with the highest oil demand shares in 2050 will be the Middle East and North Africa (19%) and Greater China (14%).

The Middle East and North Africa is the largest oil-producing region today, with a 37% share of total production. This share rises dramatically over the next three decades as other major oil-producing regions see their production rapidly declining. By 2050, The Middle East and North Africa, where extraction and production costs are lowest, is expected to dominate oil production with a 70% share.

Natural gas

The power sector would remain the primary consumer of gas, but power generation would represent a declining share in the demand from 35% today to 27% by 2050. Increasing electrification of residential and commercial heating and cooking sees will see the buildings sector's share of gas demand decline as well. As is the case with oil, non-energy use of gas as a feedstock climbs to 14% in 2050 since feedstock use is a lesser source of emissions and hydrocarbons are virtually irreplaceable in the petrochemical industry. North America is currently the world's leading producer of natural gas, accounting for more than a quarter of global production. It would concede this position to the Middle East and North Africa, due to the latter region's less-stringent climate ambitions and lower extraction costs.

FIGURE 3.4

World coal demand by sector

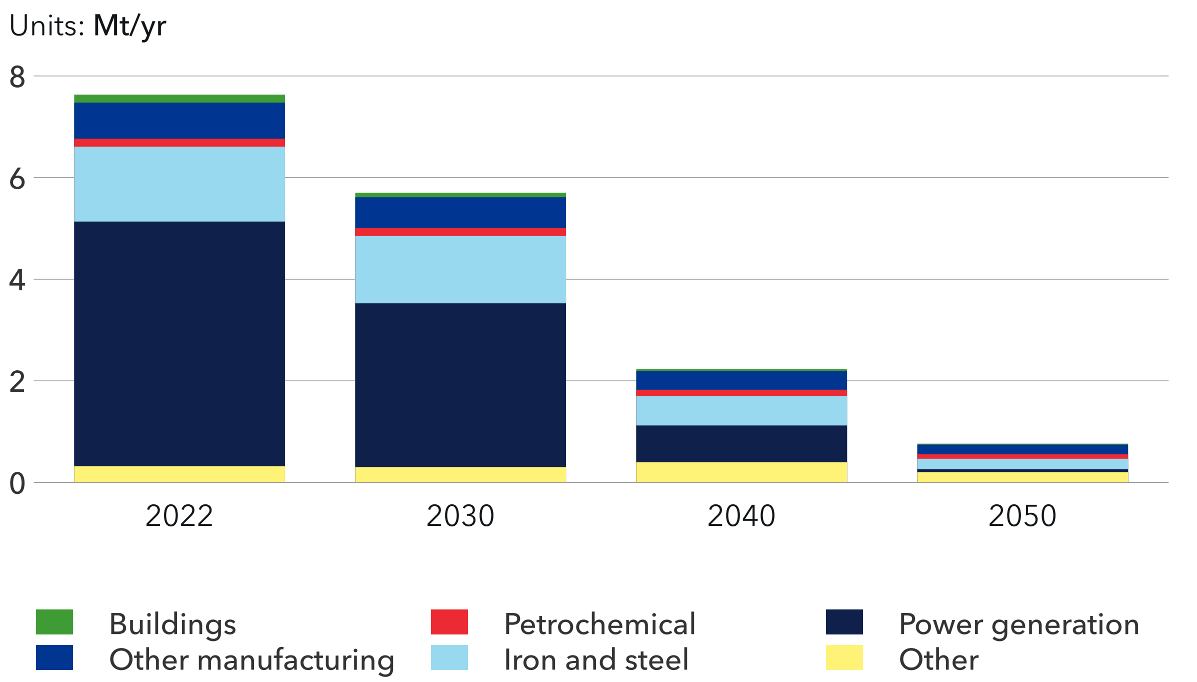


FIGURE 3.5

World oil demand by sector

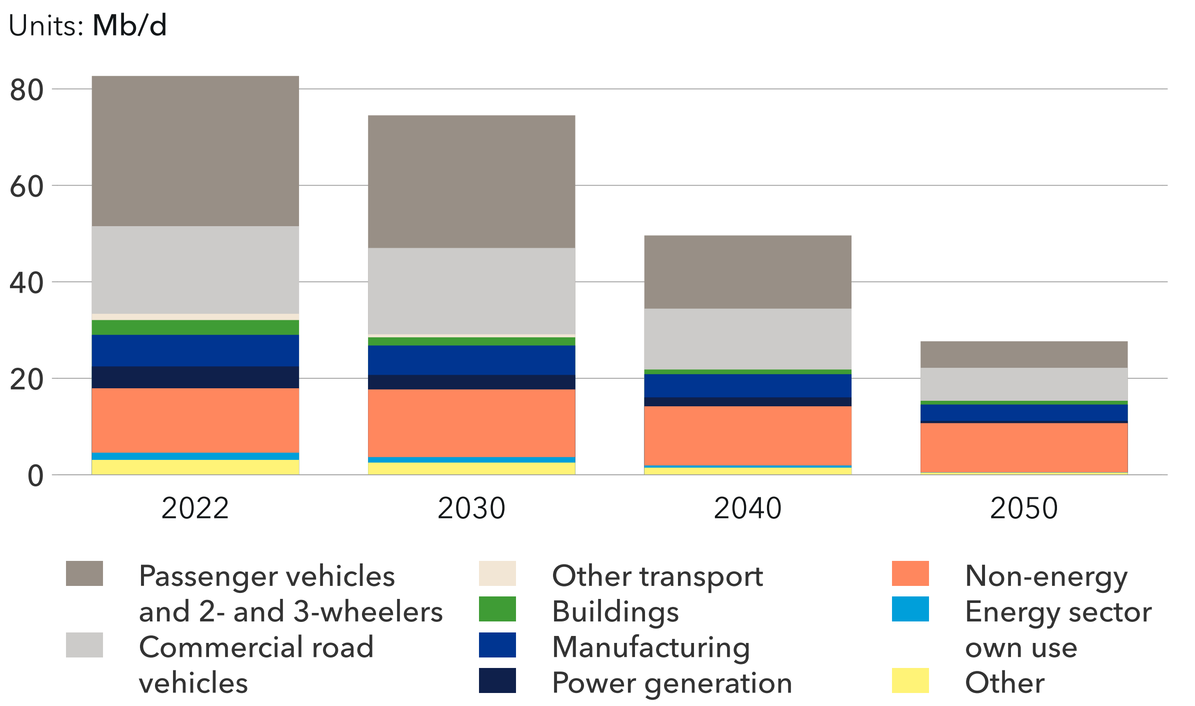
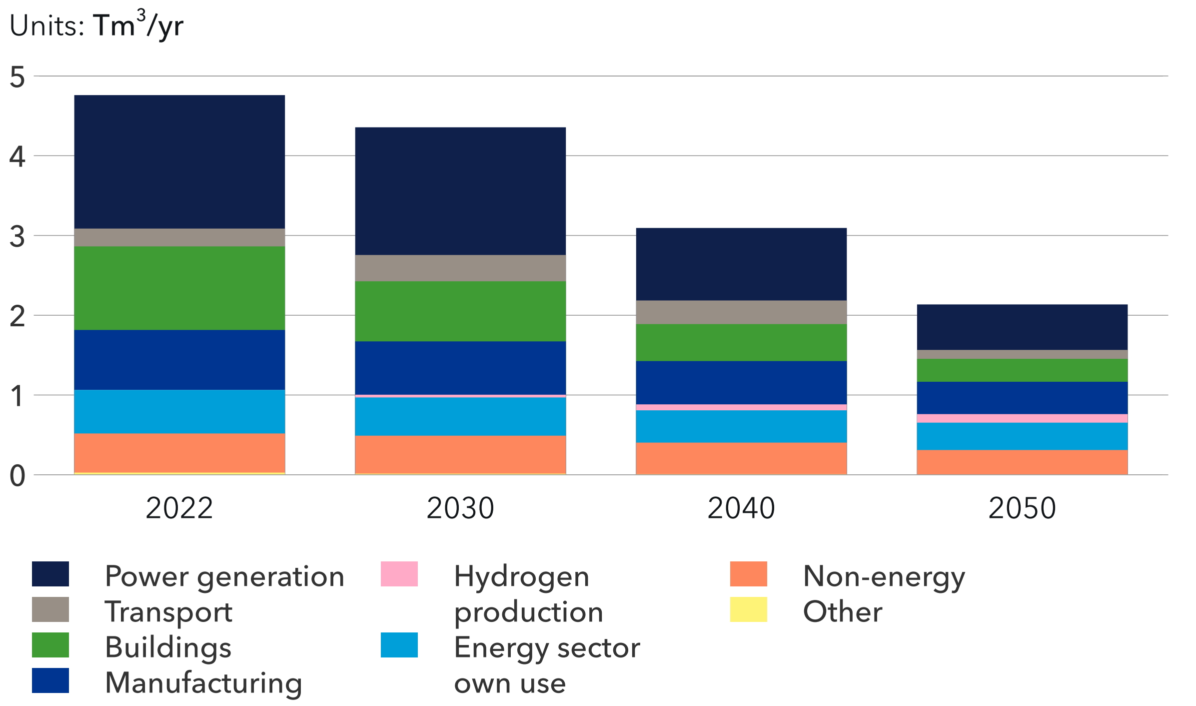


FIGURE 3.6

World natural gas demand by sector



3.3 SOLAR

PNZ	Share in primary energy	1% in 2022	28% in 2050
PNZ	Share in electricity production	5% in 2022	37% in 2050

Direct and indirect electrification is a key feature of our pathway, and there is probably no other renewable technology that can match the potential of solar PV. Together with wind, solar PV is already the cheapest generator of new electricity in most places in the world, and costs continue to fall rapidly as manufacturing capacity ramps up.

As a result, solar PV overtakes oil in our PNZ as the main primary energy supply source by 2040 and represents a bigger share than all fossil fuels combined by 2050. About a third of the installed capacity is dedicated to off-grid hydrogen production and the rest is grid-connected. In 2032, solar PV overtakes gas-fired electricity to become the largest source of electricity globally, before being overtaken by wind in 2037.

The intermittency challenge of solar would be partially solved by comprehensive installations combining solar PV with storage to access higher capture prices when supply is lower, such as at night. 40% of grid connected solar PV installations are co-located with storage by 2050.

A tripling of annual capacity addition by 2030
Though impressive, this growth rate seems achievable. In 2011, capacity additions were only at 30 GW/yr, about one ninth of 2022 levels, and there is already today significant production overcapacity in China that could be mobilized in the short term (IEA, 2023). This is why the 2030 capacity addition target is 'only' 40% higher than in our ETO forecast. There should however be an intensive scale-up along the entire supply chain, especially in regions wanting locally-sourced solar panels.

However, even if adequate manufacturing capacity is built, significant challenges will arise for permitting and grid-connection at the pace required in our PNZ. In that regard, solar PV plants with their high modularity and flexibility show clear advantages over wind and other renewable solutions. Besides utility-scale installations, solar PV systems can also be installed on rooftops, optimizing land use.

50% of capacity to be installed in China and Indian Subcontinent by 2050
Today, Greater China has the largest share (35%) of solar PV capacity among our regions. In our PNZ, Greater China dominates capacity additions in the years up to 2030, following which the Indian Subcontinent progressively overtakes it for grid-connected electricity generation. Two regions, South East Asia and the Middle East and North Africa, also see substantial growth from the late 2030s.

Nevertheless, Greater China would have the largest grid-connected capacity in the world by 2050. It also shows by far the highest off-grid capacity for hydrogen production with a huge ramp-up in the 2030s. The current industrial base in the region supports this global dominance and preference for solar PV.

There is a small amount (0.5 PWh per year) of off-grid production by 2050, mainly in Sub-Saharan Africa and the Indian Subcontinent, supplying electricity to rural districts for lighting, mobile charging, and other smaller end uses. Such off-grid installations, though marginal in energy terms, are extremely valuable from a sustainable development perspective.

FIGURE 3.7
Solar PV capacity addition and electricity generation

Units: GW/yr; PWh/yr

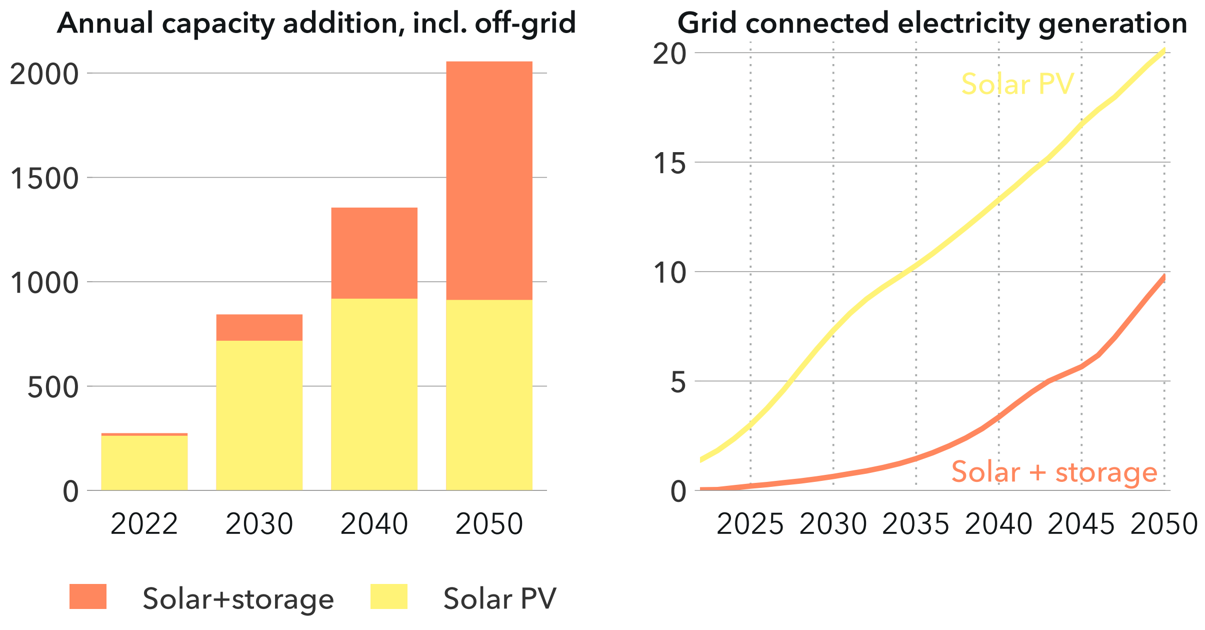
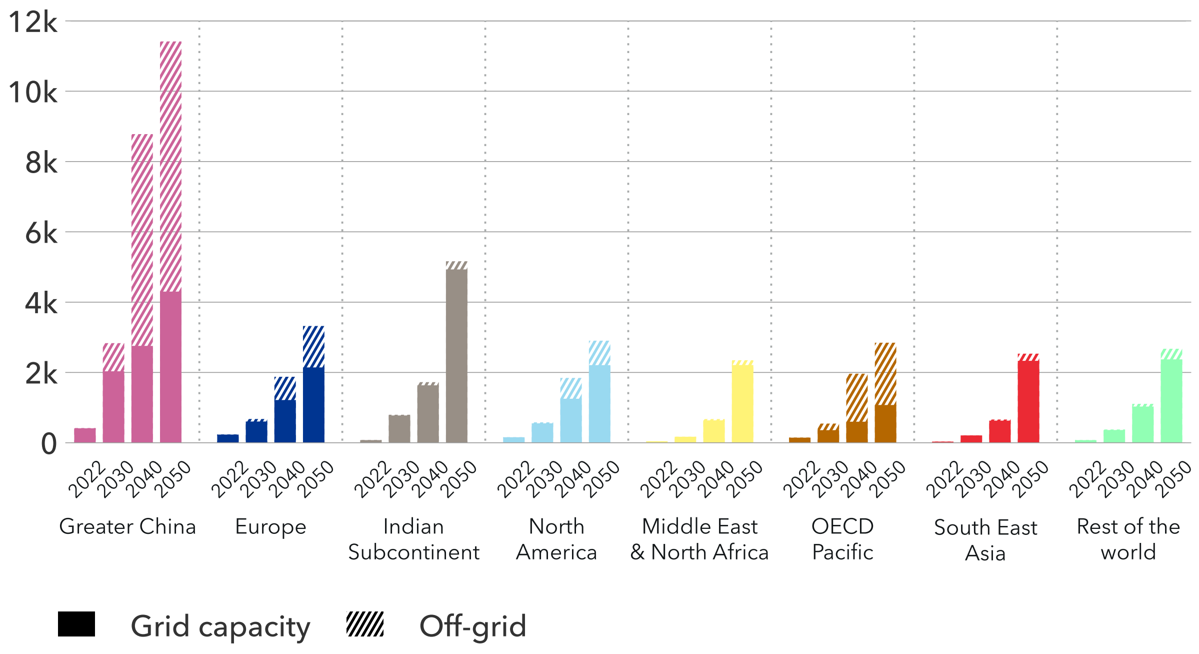


FIGURE 3.8
Solar PV installed capacity by region

Units: GW



3.4 WIND

PNZ	Share in primary energy	1% in 2022	23% in 2050
PNZ	Share in electricity production	7% in 2022	36% in 2050

By mid-century, wind is the second largest provider of primary energy in our pathway, with a higher supply than all fossil fuels combined, and is the largest grid-connected electricity source. This is a big step up from our ETO forecast, in which primary energy supply from wind is about half this in 2050.

We consider three categories of wind power plants: onshore wind, fixed offshore wind, and floating offshore wind. Of these, onshore wind power grows 37-fold between 2022 and 2050. Fixed offshore, which starts from a much lower base, increases its share in the electricity generation mix from 0.6% in 2022 to 8% by 2050. Of the three, floating offshore wind is the least mature and has 2.5% share in electricity generation in mid-century.

Globally by 2050, the combined on-grid and off-grid power system capacity in our pathway consists of 11.1 TW of onshore wind, 2.4 TW of fixed offshore wind, and 0.6 TW of floating offshore wind.

A quadrupling of capacity addition by 2030

A considerable amount of new wind power capacity needs to be installed every year from now on to generate the levels of power needed in our PNZ. This would need considerable effort to improve permitting and grid-connection processes.

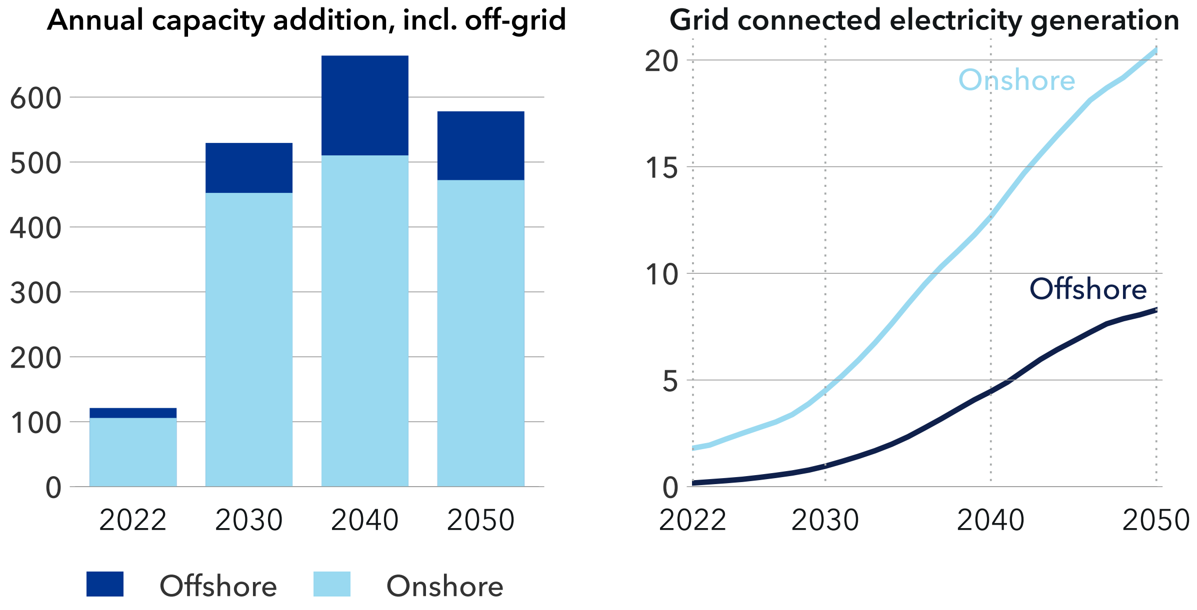
From 2023 to 2030, for every GW of offshore wind power, 5 GW of onshore wind power plants are built on average. However, competition for suitable land would increasingly impact onshore wind costs, while offshore wind costs would decline rapidly. Thus, regions such as North America and Greater China progressively start investing more in offshore wind power plants. From 2035 onwards, for every GW of offshore wind power plant, only 3 GW of onshore wind power plants are built worldwide. Such a massive development in fixed offshore wind translates to higher investment in new electricity-grid lines, especially in undersea cables. The short-term headwinds in the wind industry would also need to be resolved very quickly.

In addition to the grid-connected wind capacity described above, about 3.6 TW of wind capacity is built for dedicated hydrogen production as off-grid capacity between now and 2050.

FIGURE 3.9

Wind capacity addition and electricity generation

Units: GW/yr; PWh/yr



China dominates grid-connected capacity, Europe off-grid

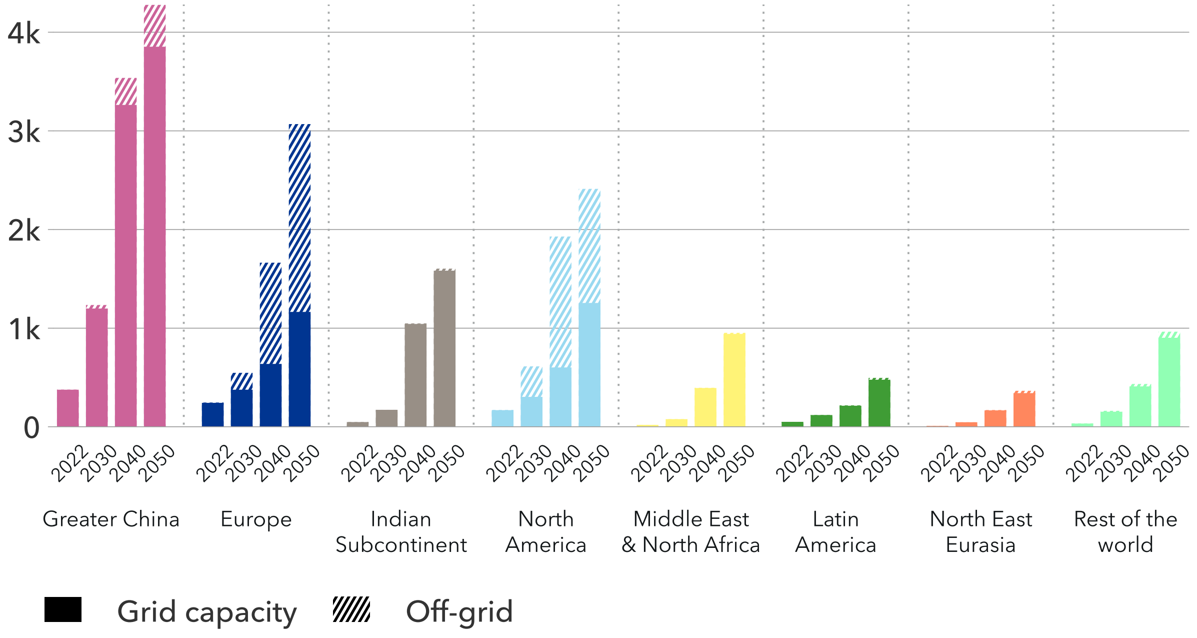
Greater China is the world's biggest generator of wind power today and remains so in our PNZ through to 2050 when its share of installed grid-connected wind power generating capacity is 36%. North America and Europe are second and third in 2050, respectively. Capacity additions in these three leading regions trigger steeper cost reductions for wind power, which also drives significant wind generation development in other regions including some not yet invested in wind power. These other regions include South East Asia and OECD Pacific. North East Eurasia would be an outlier, adding very little wind-powered electricity generation.

In our PNZ, most of the off-grid capacity for hydrogen production is in Europe, followed by North America and Greater China.

FIGURE 3.10

Wind installed capacity by region

Units: GW



3.5 OTHER NON-FOSSIL ENERGY SOURCES

PNZ	Share in primary energy	17% in 2022	29% in 2050
PNZ	Share in electricity production	27% in 2022	19% in 2050

Bioenergy

In the PNZ, bioenergy has to assume increasingly greater importance because there are no easy alternatives to thermal power plants, which are crucial for regions such as North East Eurasia and, in the medium term, in the transport sector. Bioenergy in annual primary energy supply increases from 59 EJ in 2022 to 97 EJ by 2050.

Bioenergy undergoes a sectoral shift to 2050. In 2022, buildings was the largest demand sector for bioenergy (46%). Due to electrification and hydrogen use in buildings, this share drops to 26% by 2050. In contrast, the PNZ has heat-only power plants and manufacturing increase their bioenergy use. In North America, for example, 36% of bioenergy demand in 2050 is in the manufacturing sector, at which time 79% of such demand in North East Eurasia is from power plants. The absolute demand for bioenergy in the transport sector grows from 5 EJ in 2022 to 6 EJ in 2050. This is in stark contrast to our ETO forecast where the demand doubles to 11 EJ by 2050: to achieve net zero, more bioenergy needs to be used in hard-to-abate sectors like aviation, manufacturing, and heat-only plants. Such use in point-emission installations also makes bioenergy with carbon capture and storage (BECCS) possible, enabling net-negative sites. Bioenergy is less important in decarbonizing transport, where electrification is a better solution to achieve net zero in road transport, and for making ammonia and e-fuels for maritime transport.

Nuclear

Presently there is dramatic nuclear power cost increases in construction, build-out, planning, and waste disposal in Europe, North America, and OECD Pacific. At the same time, nuclear power plants are far from as reliable an energy source as is often claimed, with utilization rates lower than 50% in summer 2022 in several jurisdictions. Maintenance issues, climate-induced lack of cooling water, and supply-chain disruptions are just some examples impacting this development.

However, nuclear power is a low-carbon technology with many advantages in a PNZ. It has limited land use, increases supply-chain resilience by requiring different raw materials than renewables, and is often associated with greater energy security. Yet, the required technological know-how and the uncertain future of small modular reactors (SMRs) limits the number of countries where massive development can occur.

As a result, although it cannot directly compete against the large cost decrease and fast development of solar PV or wind, nuclear power generation doubles between now and 2050 in in our PNZ reaching 5900 TWh/yr.

Hydropower

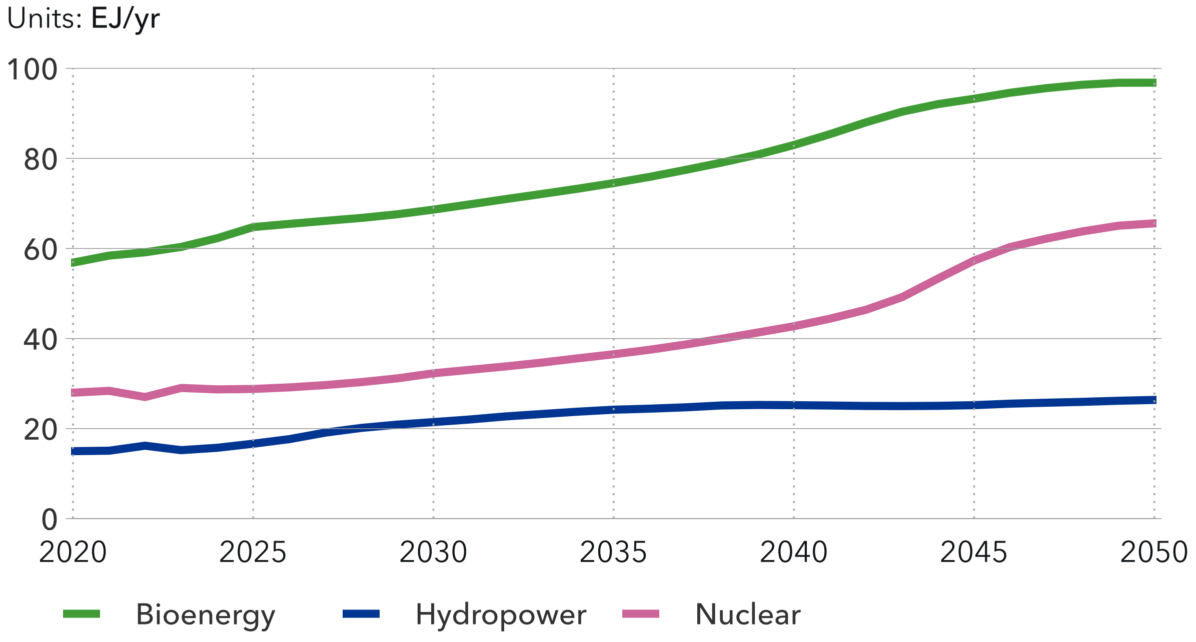
Hydropower has historically been the largest renewable electricity source, a role it retains today. Hydropower provides many services to a power system: it is usually a source of cheap and flexible electricity, and pumped hydro currently represents more than 98% of the global electricity-storage capacity.

However, the potential for new hydropower development is limited by natural constraints, and generation increases by 70% between now and 2050, reaching almost 7 PWh in mid-century, driven by significant growth in Greater China, the Indian Subcontinent, and Sub-Saharan Africa. This is just 10% above our ETO's 'most likely' forecast, underlining the limited additional impact of hydropower in our pathway.

Interestingly, hydropower is highly sensitive to climate change, as extreme weather events (droughts and heavy rains), glacier melting, and decreased snowfalls all have a negative influence on the production output. As time goes by, we can expect that hydropower will perform better in our pathway than in a world above 1.5°C.

FIGURE 3.11

World bioenergy, hydropower, and nuclear supply



Historical data source: IEA WEB (2022)

3.6 HYDROGEN +

Essential for decarbonizing hard-to-electrify sectors

Low-carbon hydrogen is an integral part of net-zero strategies being developed by many countries and is urgently needed for the decarbonization of hard-to-abate sectors. Accordingly, hydrogen and derivatives have a far higher share of final energy demand in our PNZ (15%) than in our ETO forecast (5%) by 2050.

More than a fourth of global hydrogen and synthetic fuel demand by 2050 is used for industrial heating. By 2050, 28 EJ/yr of energy demand in manufacturing is supplied by hydrogen, a 22% share among energy carriers used in manufacturing.

By 2050, pure hydrogen accounts for 7% of road transport energy demand, despite significant subsidies assumed in our PNZ. This relatively small share is the result of the competitiveness of battery-electric propulsion in all segments of road transport.

The story is different in maritime transport. The absence of a significant battery-electric option for most parts of maritime transport leaves synthetic low- and zero-carbon fuels as viable options for decarbonization, leading to hydrogen derivatives supplying 72% of the maritime fuel mix by 2050 in our PNZ. Global aviation also sees a significant share (40%) of pure hydrogen and hydrogen derivatives in its fuel mix.

The development of electrolysis

The share of fossil-based hydrogen declines from almost 100% to about 15% by 2050, and no unabated installation remains. By mid-century, the highest share of hydrogen production comes from dedicated off-grid capacities (74%), led by dedicated solar PV.

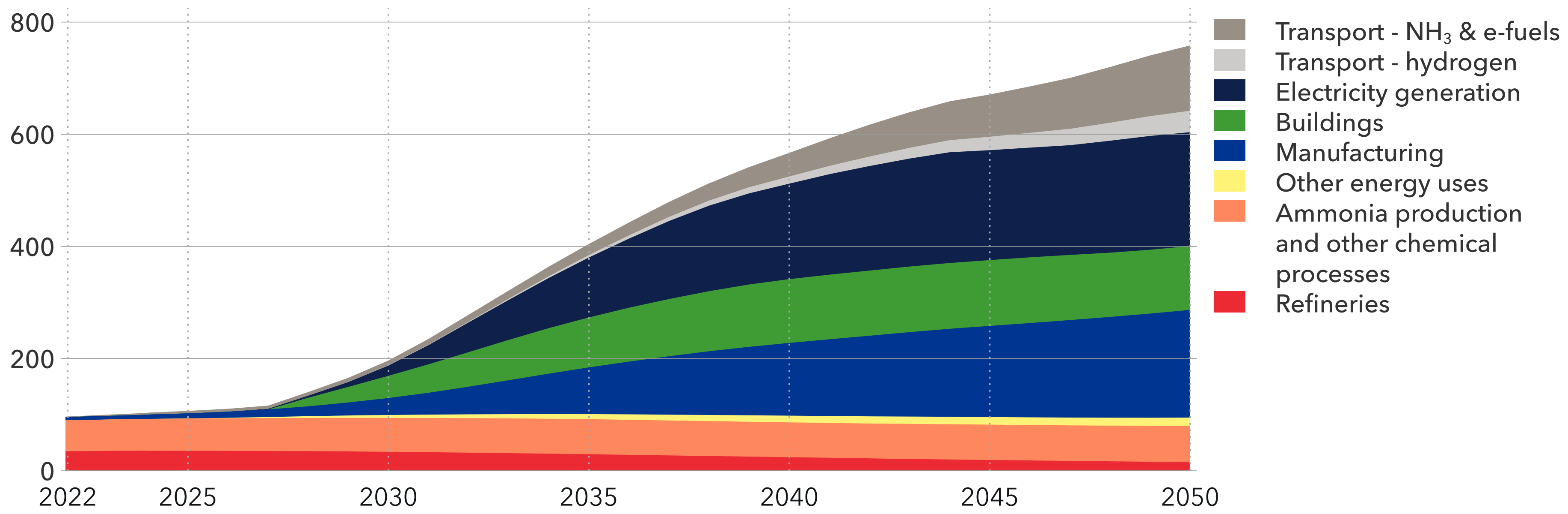
Global hydrogen production needs to scale significantly. Electrolysis capacity for dedicated off-grid hydrogen production needs to be 0.4 TW in 2030, 1.9 TW in 2040, and 3.8 TW by 2050, led by Greater China and Europe. Grid-based electrolysis needs to follow this capacity ramp-up with capacity at almost 2 TW by 2050. Here, the development is led by North America and Europe. Total hydrogen production (including feedstock) in 2050 at 820 Mt/yr under our PNZ compares with 350 Mt/yr forecast by our ETO for the same year.

By 2050, around 15% of hydrogen production goes to hydrogen derivatives as fuel. Interestingly, natural gas with CCS is the preferred route for ammonia production, as the current production process is well-suited for efficient carbon capture.

FIGURE 3.12

Global demand for hydrogen and its derivatives by sector

Units: MtH_2/yr

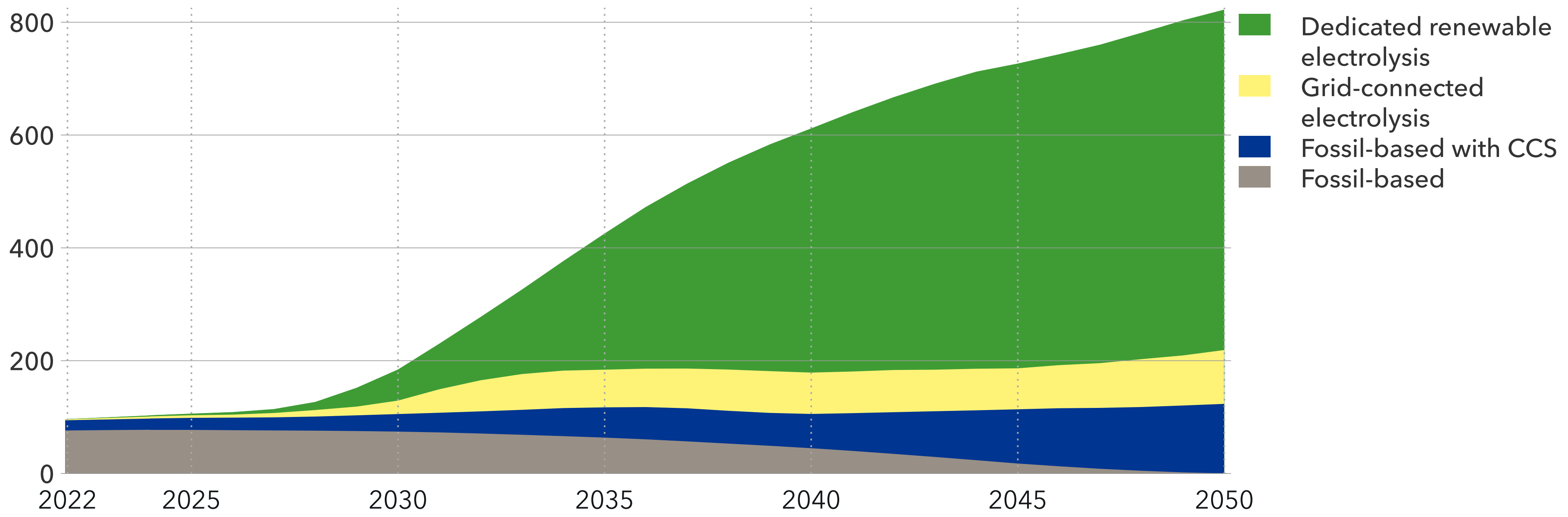


All non-transport uses are pure hydrogen.

FIGURE 3.13

Global production of hydrogen and its derivatives by production route

Units: MtH_2/yr



3.7 TECHNOLOGY CHALLENGERS

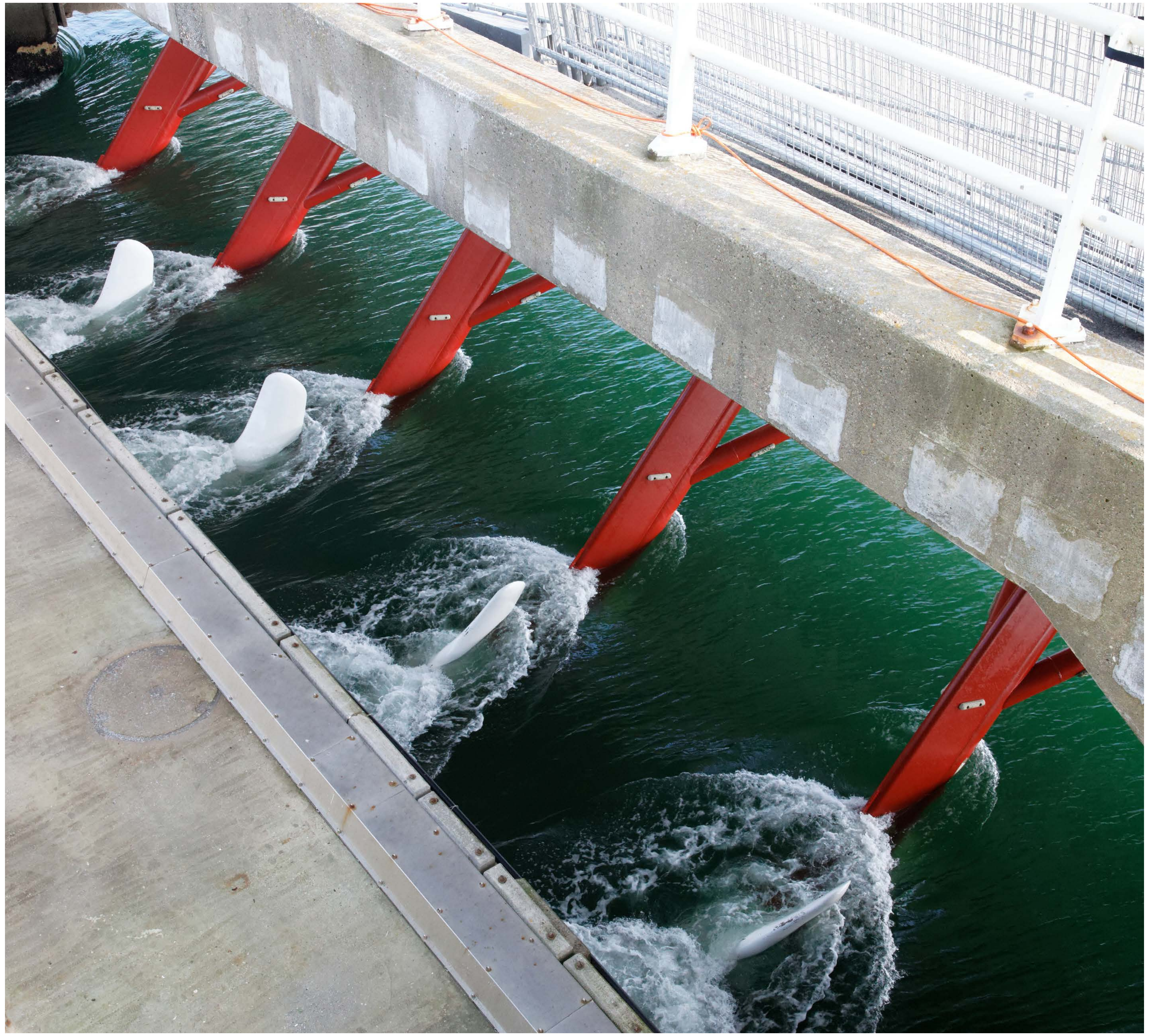
Even in our pathway to net zero, other renewable energy sources are likely to remain marginal on a global scale between now and 2050. We do not model concentrated solar power (CSP); in our pathway, geothermal and solar thermal combined provides less than 2% of world primary energy by mid-century – geothermal power at 9,000 PJ/yr and solar thermal at 250 PJ/yr. This is around the same amount of solar PV that we see in world primary energy today, but our net-zero scenario expects this energy carrier to grow to 28% (186,000 PJ/yr) by 2050. Solar thermal use in energy demand actually decreases throughout our pathway period, as it is mainly used in buildings in China for water heating, which electricity will take over.

Other potential future energy sources consist of technologies which are not yet proven and marginal technologies that are not expected to scale by 2050. Ocean energy is one of these marginal technologies. Among several types of ocean energy technology, the most highly developed today have a combined capacity of about 536 MW. The LCOEs and investment costs of these technologies are declining but remain higher than for other forms of renewable energy, and there are other barriers to ocean energy's widescale adoption.

Another energy source we do not see emerging is nuclear fusion. Several promising research projects focusing on smaller fusion systems are currently being piloted and a nuclear fusion reaction produced more energy than it took to drive the reaction for the first time in December 2022. Even with this breakthrough, there will still be a significant delay before energy on a scale comparable with other power sources will be provided. Therefore we confine our pathway to traditional fission technologies.

During the period covered by this pathway, one or more of the emerging energy technologies may achieve a breakthrough such that they become cost competitive. However, to have a significant impact on the energy system, they would need to grow much faster than incumbent renewable technologies. We do not see this happening at scale and have therefore excluded emerging technologies from the pathway. That is not to suggest that R&D effort on these technologies should be abandoned; to the contrary, promising technologies such as SMRs or wave-powered offshore desalination could make a considerable contribution to post-2050 non-fossil energy.

AI developments have received a lot of attention lately and show considerable potential to improve energy production and use, provided safety concerns are addressed (Bengio et al., 2023), but we have not quantified this effect in our PNZ.



3.8 ELECTRICITY

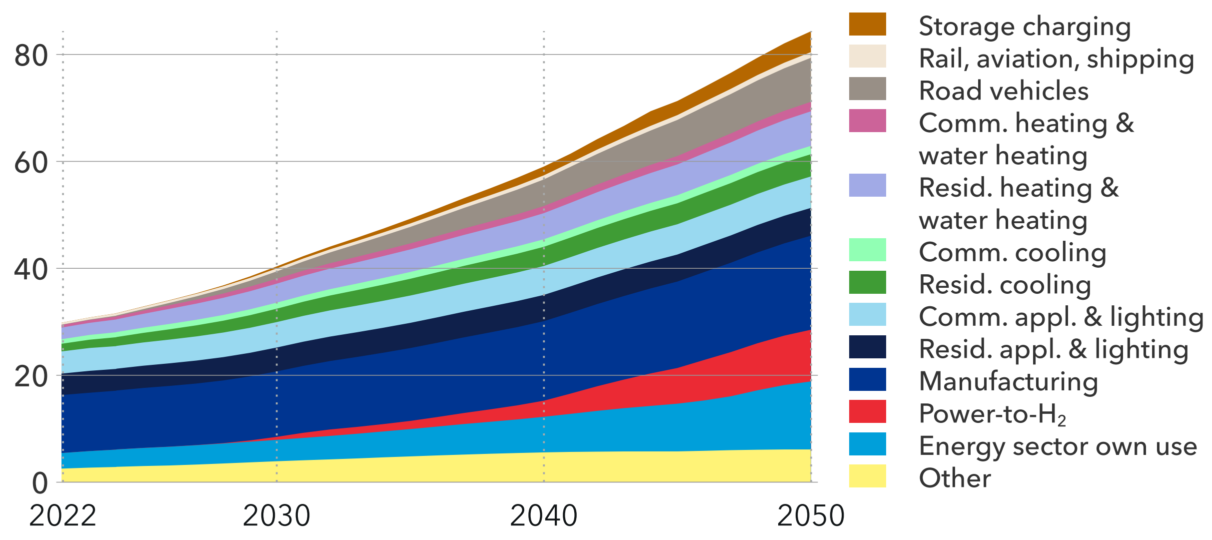
Massive direct and indirect electrification is a key pillar for reaching net zero
The electrification of the energy system is essential for unlocking higher energy efficiencies. Combined with the fast decarbonization of the power mix, electrification is the prime factor driving down emissions in our pathway. As a result, global electricity demand, including electricity demand for grid-connected H_2 electrolysis, is 84 PWh per year in 2050, almost three times what it was in 2022. Moreover, the PNZ electricity demand is 31% higher than the projected ('most likely') forecast.

The largest increase is in demand for power for electrolysis of hydrogen. From very low levels today, electrolysis demand for power supplied through the grid or from dedicated off-grid renewables is 11% (25 PWh/yr) of total demand in 2050.

FIGURE 3.14

World electricity demand by sector

Units: PWh/yr



The transport sector sees the next highest growth in demand (21-fold) for electricity, where electrification of vehicles is an important lever, especially in road transport. Transport's share in electricity demand grows from 1% in 2022 to 25% by 2050.

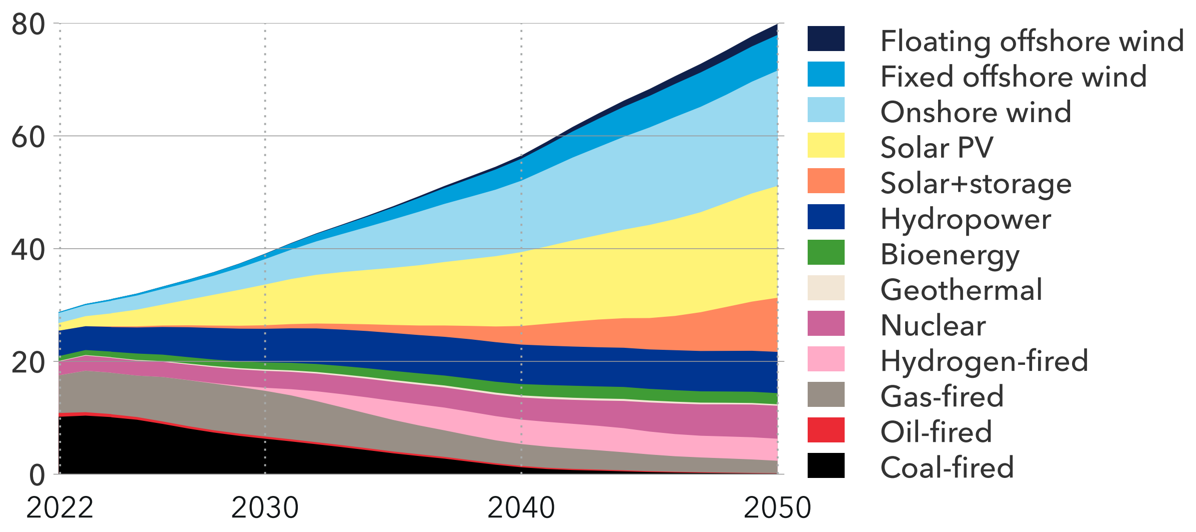
Wind and solar with the lion's share, and no more unabated fossil-fired plants
To meet the demand, grid-connected electricity supply grows to 80 PWh/yr in 2050. This is a 26% higher value than in our ETO forecast.

Phase-out of coal starts in some jurisdictions before 2030, with increased demand provided chiefly by solar and wind. Solar electricity sees a 27-fold increase between 2022 and 2050, while wind electricity rises 15-fold over the same period. Solar and wind account for 73% of electricity by 2050, 6% higher than in our ETO forecast. In total, non-fossil sources (renewables and nuclear) account for 92% of electricity generation mid-century, with the rest coming from gas-fired power plants.

FIGURE 3.15

World grid-connected electricity generation by power station type

Units: PWh/yr



Natural gas does not completely disappear from power generation. However by then, about a half of gas-fired power plants run instead on hydrogen, with a maximum volumetric blending ratio of 80% hydrogen.

The off-grid rural solar capacity in the world is 236 GW in 2050, chiefly installed in Sub-Saharan Africa and the Indian Subcontinent. Off-grid dedicated renewable capacity for electrolysis grows from very small levels in 2020 to 15 TW by 2050. Of this dedicated renewable capacity, one fourth will be offshore and onshore wind and three-fourths will be solar-based electrolysis.

Development of grids and storage solutions must follow the pace
There is a recurring concern that power systems highly reliant on VRES are not resilient enough. There is indeed a need for new balancing mechanisms and technologies, but this is not necessarily where the major challenges will lie for the grids (see next page).

Already today, a large number of renewable developments are slowed down if not cancelled due to gridlocks (DNV, 2023). The doubling of grid capacity addition requires significant streamlining and acceleration of permitting and grid-connection processes. Scaling up supply-chains for grids build-out and utility-scale storage is also where challenges are expected. From a few dozen GWh today, battery storage would need to scale up rapidly to meet the necessary demand in our pathway, with a 200-fold increase to 3,400 GWh of grid-connected capacity (including battery from road vehicles) already by 2030.

Yearly grid capacity addition in the next decade compared to the last decade		**2 times higher**
Global utility-scale storage capacity	**8 TWh 2030**	**80 TWh in 2050**

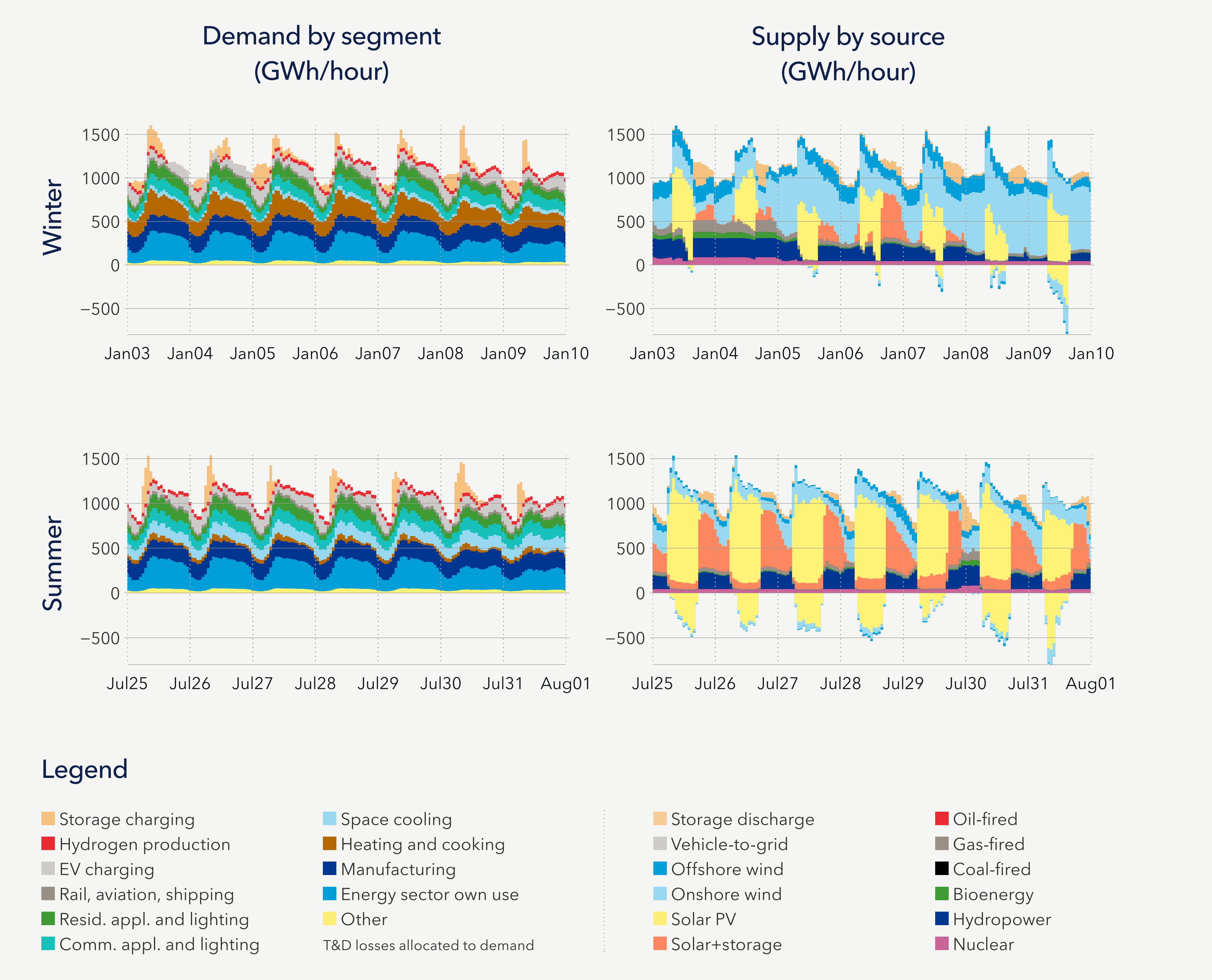
THE CHALLENGES OF NET-ZERO POWER GRIDS

In our PNZ, the 2050 power grid faces numerous challenges:

- Adequacy: Ensuring there is always enough energy to satisfy demand. This is particularly evident when comparing demand peaks to dips in renewable generation, such as during cloudy days with scarce solar or calm days with minimal wind.
- Flexibility: The grid needs to swiftly adjust to varying supply, especially from inconsistent renewable sources like solar and wind.
- Reliability concerns with variable renewables: Solar and wind, essential for a green transition, raise reliability issues. When these sources cannot meet demand due to inadequate sunlight or wind, backup systems (e.g., storage or conventional plants like gas or nuclear) must fill the gap. Conversely, when there is an abundance of renewable energy, mechanisms are needed to store or redirect the excess. Solutions include battery storage, pumped hydro, hydrogen production, and demand response methods such as strategic EV charging and energy trading. Even with high renewable incorporation, there may be occasions when solar and wind are curtailed because it is not cost-effective to utilize the excessive output for only short periods annually.

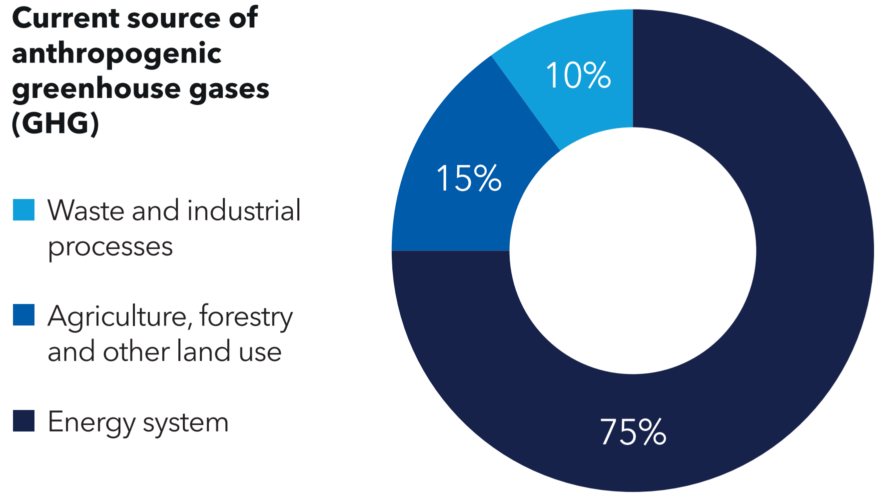
The charts depict the weekly how the electricity demand and supply would behave for North America during a winter and a summer week in 2050. A daily demand pattern is evident in both weeks, with demand peaks occurring during the day. While the manufacturing sector's load remains fairly consistent between seasons, the buildings sector shifts from winter space heating to summer cooling demands.

Solar PV consistently supplies power during daylight hours in both weeks, but wind supply varies without a clear daily pattern. Notably, solar energy has a greater impact in the summer, whereas wind energy is more abundant in the winter. During times when both solar and wind outputs are low, storage solutions and other flexible power sources compensate for the shortfall. In the summer week, there is a noticeable fluctuation in output from traditional power sources, highlighting the need for increased flexibility.



3.9 EMISSIONS

Current source of anthropogenic greenhouse gases (GHG)



Net-zero emissions, carbon budgets, and the 1.5°C target

The pathway to net-zero emissions is produced as a back-cast in which net-zero global CO_2 emission is achieved in 2050 from a starting point of 41 $GtCO_2$ in 2022. This number includes emissions from the energy system and process-related emissions – such as emitted during cement production – as well as from land-use changes.

The net-zero goal is often associated with limiting average global temperature increase to 1.5°C. But as crucial is the pace at which we reach net-zero emissions. This can be estimated through the carbon budget, i.e. the cumulative amount we can emit to stay below 1.5°C. In our PNZ, the current carbon budget of 280 $GtCO_2$ would be exhausted by 2030. That means that to return to a 1.5°C trajectory by 2100, the cumulative emissions between 2030 and 2050 – an 'overshoot' of some 307 $GtCO_2$ – need to be removed in the second half of this century.

In that sense, our PNZ is not the most aggressive net-zero scenario, as it already acknowledges that because of the inertia of the energy system, achieving a 1.5°C future without temporarily higher average warming is out of reach. It also implies that a continuous effort will be needed until the end of the century to achieve this target. This involves a massive carbon capture and sequestration effort. This is nonetheless an enormous task and a huge gap compared with the emission levels we forecast in the ETO.

Closing the gap

The ETO emissions forecast predicts 23 $GtCO_2$ of annual emission in 2050, showing there is a big gap to be closed to reach net-zero emissions by then. The development of CO_2 emissions is well correlated with future energy use from fossil-fuel carriers. Reducing combustion by replacing fossil fuels with electricity from nuclear and renewables can, along with improved efficiency, cumulatively cut about 235 $GtCO_2$ emissions between 2023 and 2050. Furthermore, CCS plays a decisive role in the PNZ, especially in power and manufacturing, contributing to a reduction of more than 89 Gt of emissions over that period.

FIGURE 3.16

Pathway to net-zero emissions including overshoot and gap to be closed

Units: $GtCO_2$/yr

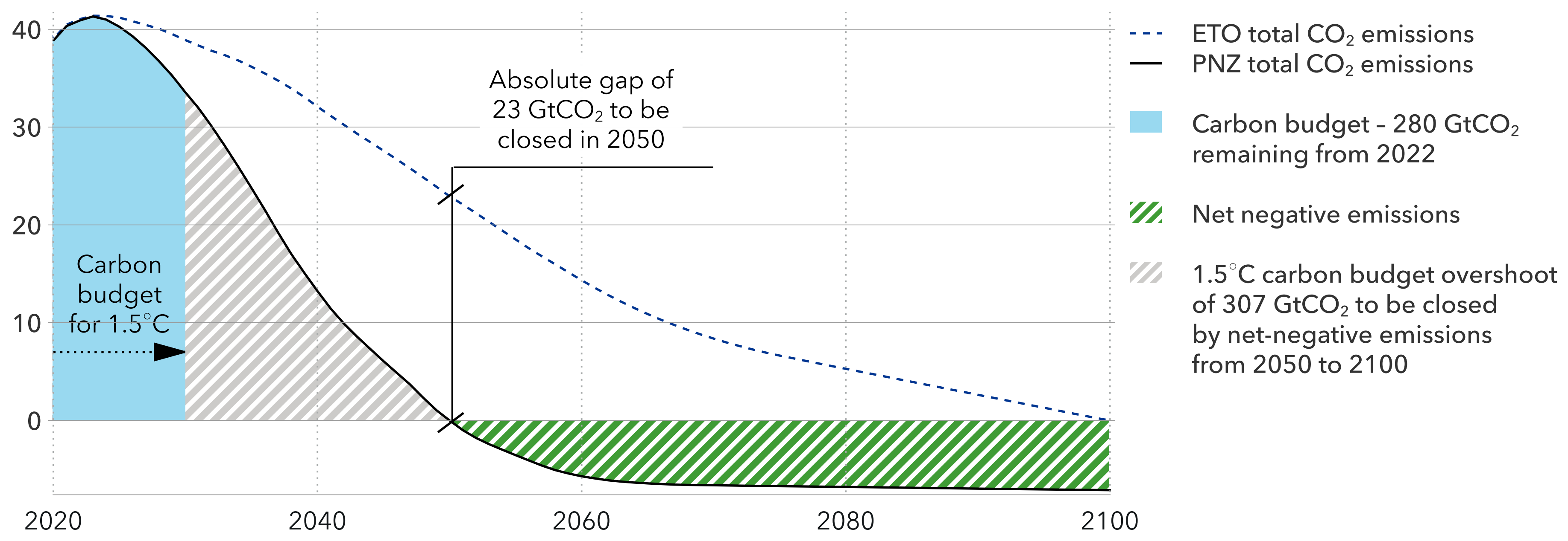
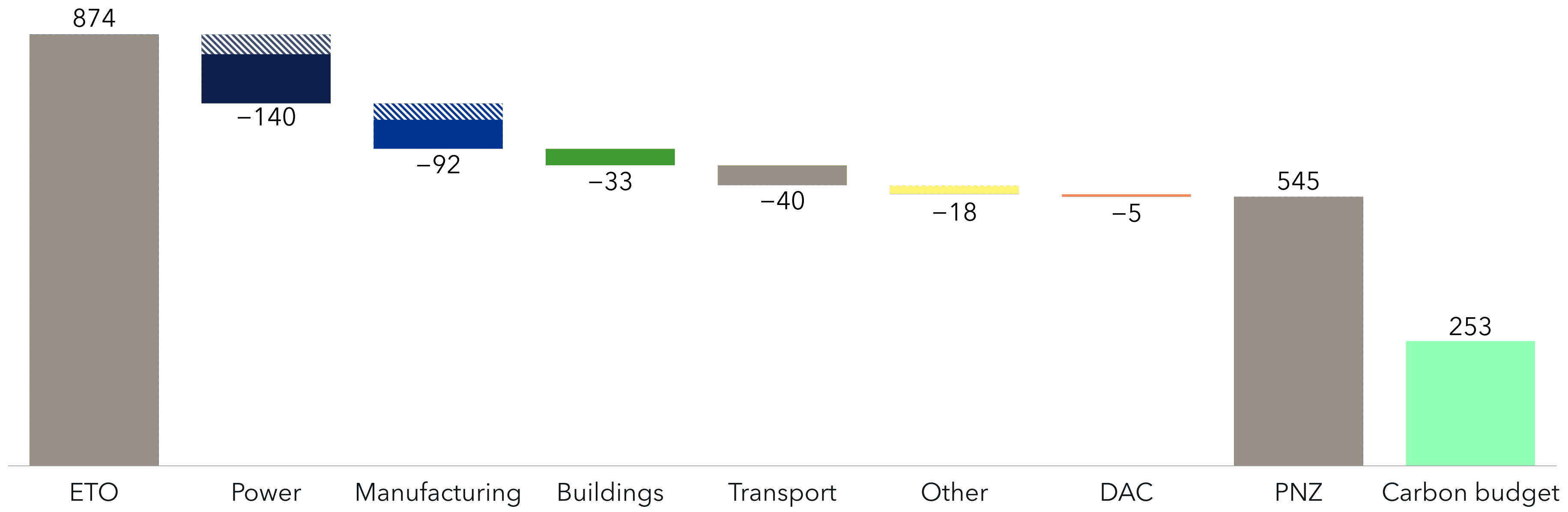


FIGURE 3.17

Reduction of cumulative emissions 2023-2050 by sector, and carbon budget

Units: $GtCO_2$



Carbon budget to limit temperature increase to 1.5°C. Plain colour: reduction through fuel switching and energy-efficiency. Hatched: reduction through carbon capture and storage

Carbon-removal solutions are essential for reaching net zero and limiting a large overshoot of the carbon budget

Assuming a continued scaling up of DAC, as well as further improvements in land use after 2050, total negative emissions must reach -6 $GtCO_2$/yr in 2060 and continue the trend to -7.1 to 2100. Cumulatively from 2050, this amounts to -310 $GtCO_2$, which would eliminate the 1.5°C carbon overshoot by 2100.

Bioenergy with carbon capture and storage – 2.3 $GtCO_2$ in 2050
Capturing and storing the CO_2 from biomass combustion in power, district heating, waste incineration, or industrial plants will be a preferred solution, as its moderate cost will rapidly be competitive against fast rising carbon prices.

As a result, captured emissions rapidly grow, reaching a plateau in the late 2030s, corresponding to the maximum amount of CO_2 that can practically be captured in large emission points.

Direct air capture – 1.6 $GtCO_2$ in 2050
Removing CO_2 from the atmosphere is an energy-intensive and costly process, at least with current industrial-scale technologies. However, the modularity and the limited physical footprint of DAC plants have a clear advantage. They provide attractive offsets for the hardest-to-abate sectors, and allow high-income regions to reach net-negative emissions.

It should be noted that technology development is still in its infancy, and it is possible that costs may sink dramatically. More economical alternatives to DAC could also be developed before mid-century, especially if massive investments are poured in carbon removal technologies.

Agriculture, forestry and other land use – 1.2 $GtCO_2$ in 2050
In addition to energy- and process-related emissions, there are significant CO_2 emissions from agriculture, forestry, and other land use (AFOLU). The historical levels of these emissions are currently estimated (Global Carbon Project, 2022) to 4 $GtCO_2$/yr today.

We need a reversal of today's land use; deforestation must be halted and significant effort put into restoration, reforestation, and biomass regrowth. Instead of the net emissions that we have today, this enables us to reach the annual removal of 1.2 $GtCO_2$/yr by 2050, growing post-2050 to remove up to 2 Gt/yr by 2100.

Non-CO_2 GHG emissions

While CO_2 represents about two-thirds of GHG emissions, what happens to other highly potent GHGs, such as methane (CH_4), is important and is considered in the IPCC carbon budgets and net-zero considerations. For instance, methane (CH_4) emissions from fossil fuels or changes in agricultural practices, including fertilizer use or aerosol emissions, have considerable influence on what net-zero CO_2 will mean in practice. We use the IPCC scenarios in line with 'very low' and 'low' non-CO_2 GHG emissions estimates, which correspond well with the very low CO_2 emissions in our PNZ. Therefore, the approach is consistent. The abatement in CH_4 emissions in our PNZ is the result of carbon prices, reduced activity levels (production of fossil fuels), and the interaction between these factors. The carbon price of CH_4 is calculated as a unit of CH_4 converted to its CO_2 equivalent (CO_2-e) using a 100-year Global Warming Potential (GWP) time horizon. Thus, calculated CO_2-e carbon prices for CH_4 are compared against the marginal cost of CH_4 abatement.

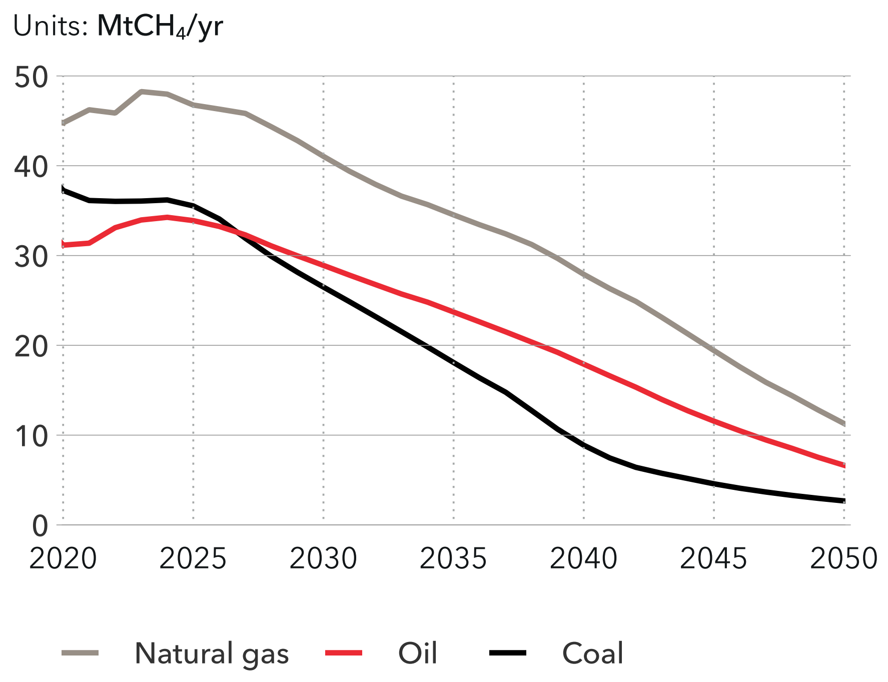
In the PNZ, CH_4 emissions from coal, oil, and natural gas reduce to 22 Mt/yr by 2050, 82% less than the 2022 level, and more than 50% less than in the 'most likely' future that our ETO forecasts. Note that the total sum of GHGs ultimately determines the global average temperature increase, and thus leads to some logical implications:

– A more aggressive reduction of GHGs in other sectors provides slightly more leeway in the energy sector and still enables a 1.5°C future.

– With less action on reducing emissions in the other sectors, achieving 1.5°C would require cutting emissions even faster and more severely in the energy sector.

However, it is beyond the scope of this report to describe how CH_4 and N_2O agricultural emissions or emissions from waste and landfills should be reduced (e.g. through a shift in dietary choices). Nevertheless, we assume a reduction in these non-CO_2 emissions in line with IPCC representative pathways for 1.5°C. However, it is clear that achieving 1.5°C is extremely difficult, and that to do so in all sectors within and outside the energy system requires everyone to act together and urgently.

FIGURE 3.18
Global methane emissions from fossil fuels



3.10 EXPENDITURES

Our pathway is affordable in the sense that it has lower costs than the present energy system. While global GDP more than doubles by 2050, global energy expenditures do not grow as fast. This disconnect is due to increasing electrification and improvements in energy efficiency, which in turn cause final energy demand to fall.

The challenge, however, is that overall costs for our PNZ are higher than those associated with the 'most likely' future we forecast in our ETO. The main obstacle does not come from energy expenditures per se, which are cumulatively only 5% higher over the 2023 to 2050 period in our PNZ. Most of the additional expenditures occur before 2040, which implies front-loading of costs which does impose a challenge, but one that is manageable. This is especially the case because from the mid-2040s expenditures are actually lower in the PNZ.

This is results from two opposing factors: by 2050, unit cost of final energy increases by 18% compared to our ETO, while at the same time energy demand is 19% lower. On a per capita basis, the variations are small compared to the growth of GDP over the same time period, as shown in Figure 3.19.

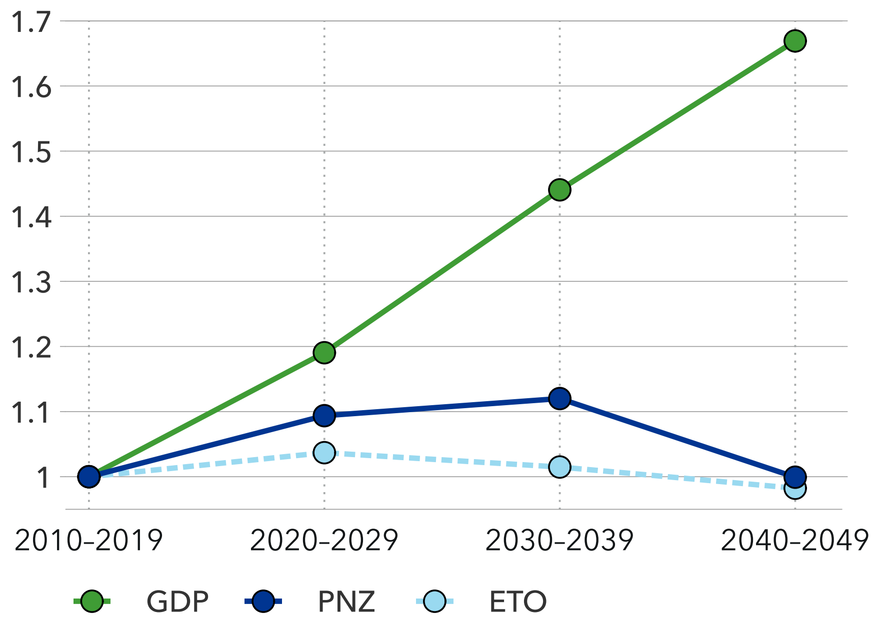
The main financial obstacle to the PNZ, therefore, does not relate to additional direct expenditure on energy production and transport/transmission. Instead, the challenge is associated with all the additional costs our pathway does not assess related to improving energy efficiency (e.g. home insulation) or low-carbon alternatives, or indeed costs associated with a just transition, including support for workers affected by the rapid displacement of fossil fuel sources. Those higher costs may be used as an excuse for inaction but are in our view far from insurmountable.

From the mid-2040s, expenditures are actually lower in the PNZ.

FIGURE 3.19

Global average energy expenditures and GDP, per capita

Units: Indexed to 2010-2019



USD 75trn investments for decarbonized energy

The breakdown of energy expenditures shown in Figure 3.20 shows that fossil expenditures drop, driven by an almost 80% decline for upstream oil and gas through to 2050. The progressive global ban on new oil and gas exploration and development means that by 2050, expenditures only relate to operating remaining production fields.

The overall picture for power generation, which drives non-fossil expenditures, is that costs shift from operating expenses – dominated by the cost of fossil fuels – to capital expenditures in renewable power and related installations. Indeed, almost no fossil fuel-fired power investment is made from 2030, and the remaining costs are for operating and maintaining those that are still running until their phase-out in the 2040s. The decline in fossil fuel-related investment contrasts with higher expenditures in low-carbon power generation. The increase in electricity demand drives non-fossil investments, which amount to some USD 53trn over the next 30 years as shown in Figure 3.21.

The doubling of electricity production and decentralization of power generation, coupled with a large amount of new VRES capacity, necessarily leads to strong investment in grids, totalling some USD 22trn over the next 30 years. Grid expenditures more than double between 2022 and 2050 in our PNZ.

FIGURE 3.20

World energy expenditures by source

Units: Trillion USD/yr

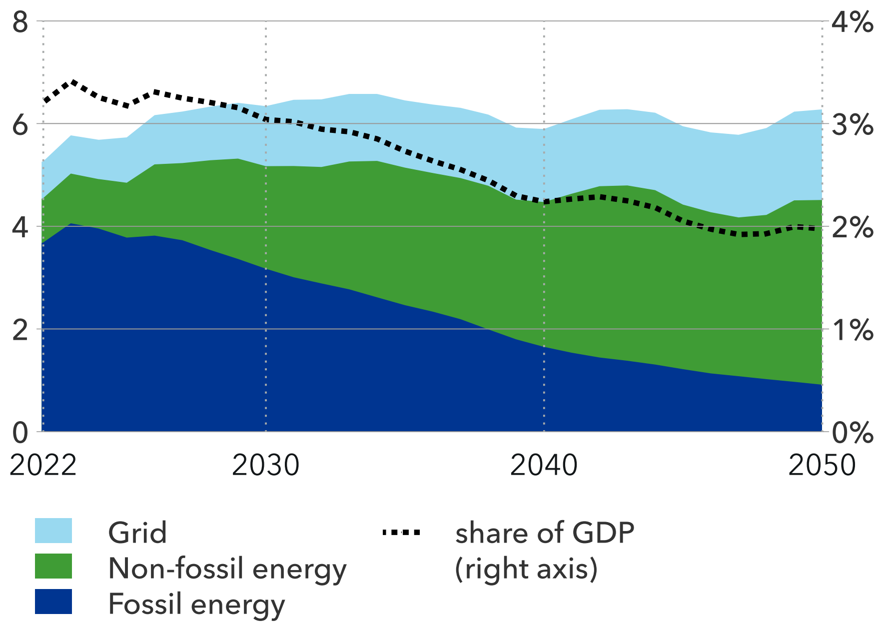
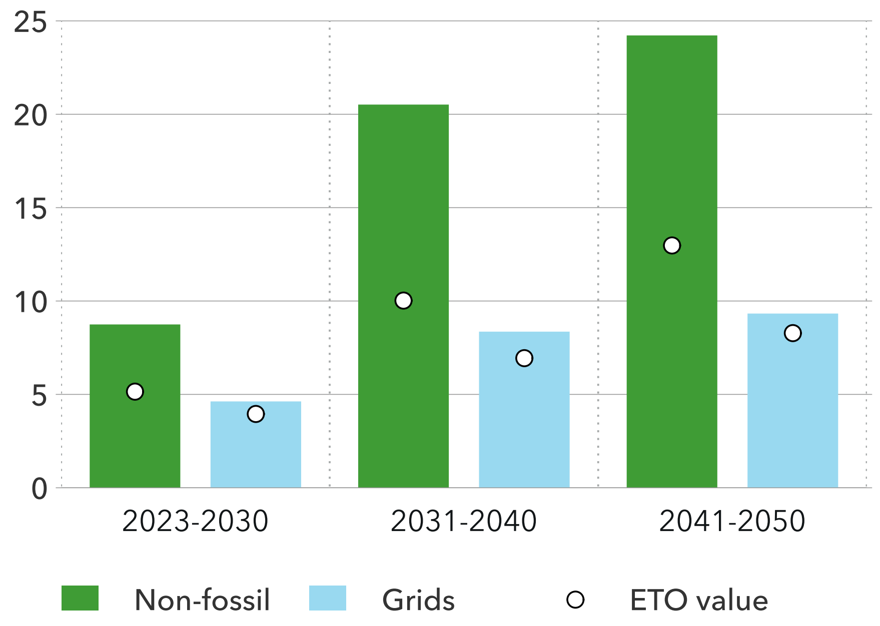


FIGURE 3.21

Cumulative investments in non-fossil energy and grids

Units: Trillion USD



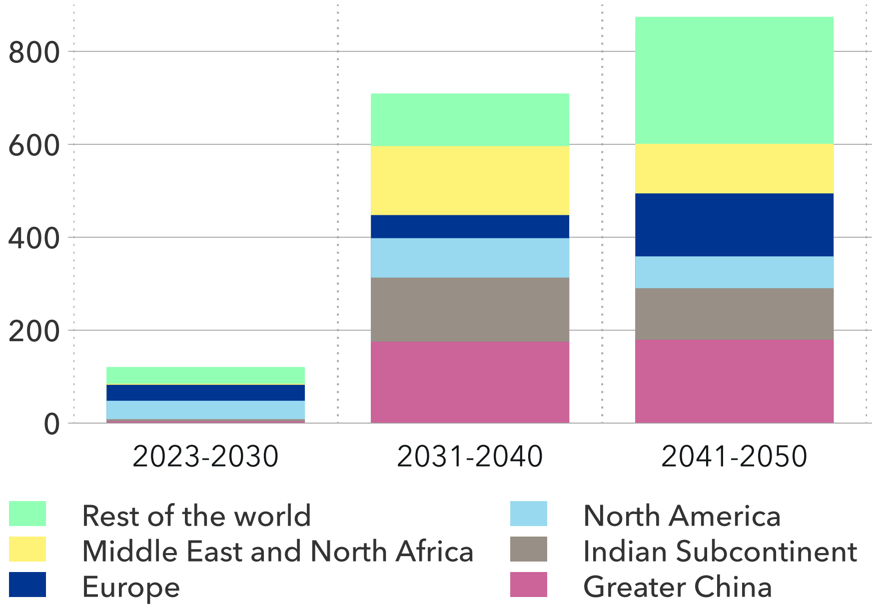
The additional costs of our pathway

Our PNZ also implies massive and immediate investments inside and outside of the energy system. Although these investments might be profitable over the long term, upfront costs and lack of visibility on the future regulations and economic situation currently favour the status quo. Cost of capital is one of the key cost drivers for capital-intensive purposes, and a common objective such as the one needed in our pathway will de-risk low-carbon technology investments. Therefore, we expect similar but stronger trends than in our ETO, with lower cost of capital for low-carbon projects, while the planned phase-out of fossil fuels increases cost of capital for fossil-based projects.

FIGURE 3.22

Cumulative investments in CCS by region

Units: Billion USD



This is decisive for capital-intensive carbon capture and removal projects, which are a key feature of our pathway. As shown in Figure 3.22, carbon capture and storage (CCS) requires early investments of more than USD 100bn by 2030. The uptake of the less efficient and more costly direct air capture (DAC) takes off later. The removal of CO_2 via DAC will represent a significant expenditure of USD 450bn per year by 2050.

Impact on households

The acceptability of the transition lies in its affordability for the population. Especially in the current inflationary period, every increase in the energy bills paid by household creates extra tension in societies, as shown in recent events in Nigeria or Kenya.

Figure 3.23 shows trends in household energy expenditures in the regions in our pathway. These household energy expenditures include CAPEX for residential space heating and cooling (such as cost of air conditioners), water heating (such as cost of heat pumps), and cooking (such as cost of electric stoves) and OPEX, which is the energy costs and energy taxes of running all the household equipment, and passenger vehicles. The impact on household energy bills varies by region.

High-income regions are front-runner regions in the energy transition, and actually see a decrease in such bills compared with our 'most likely' future from the mid-2030s. This is because they are already seeing and would increasingly benefit from the global acceleration in cost-learning curves for low- and zero-carbon technologies. Strong energy-efficiency (EVs, home insulation) measures also mean lower energy needs and thus lower energy bills.

Middle-income regions see higher expenditures during the modelled period, although the spread is important. Fossil-fuel producing regions like Middle East and North Africa often heavily support fossil fuels through gasoline subsidies for example, and the transition to electricity would increase the costs. Even if the difference between the two futures declines with time, the transition period would be sensitive, highlighting that de-risked financing from high-income regions is an integral part of the presented pathway to net zero.

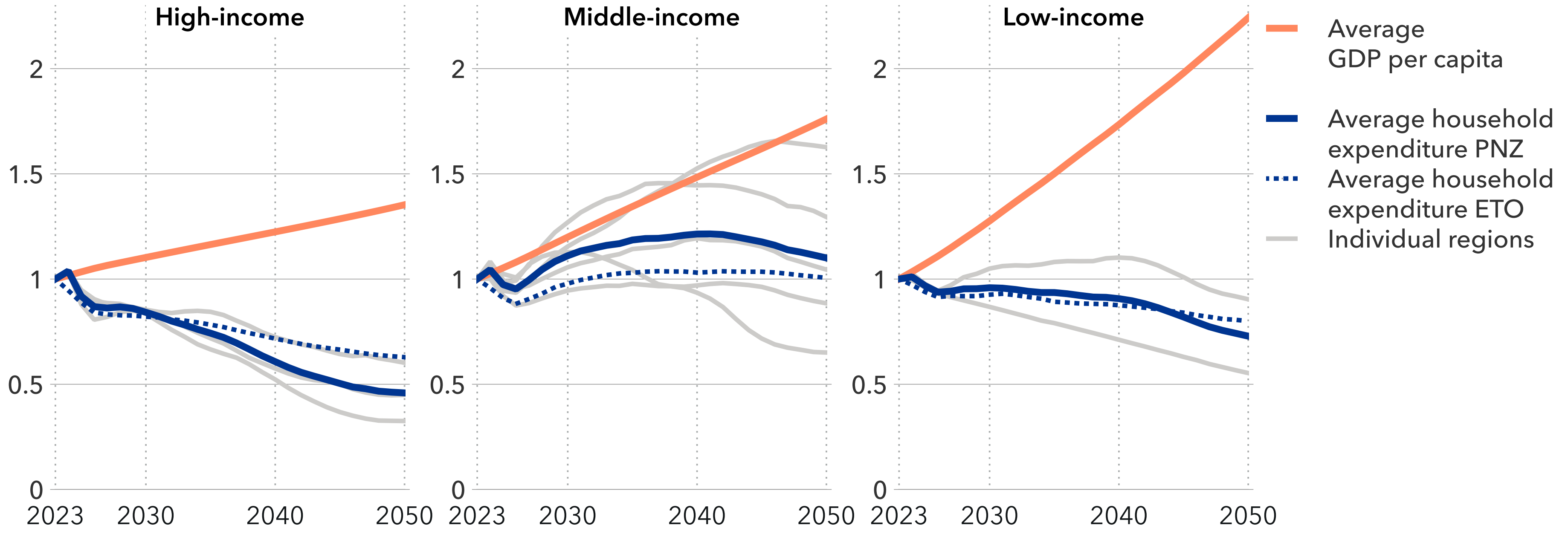
Low-income regions see a similar trend to that described in our most-likely future. This is explained by the low household energy consumption in these regions, with limited access to personal cars and water and space heating already relying primarily on bioenergy and electricity in our most-likely future.

Importantly, the growth of GDP per capita would outpace any increase in household expenditures across all of the world regions we model, clearly showing the capacity for societies to accommodate higher expenditures, through subsidies for the lower-income households for instance.

FIGURE 3.23

Evolution of household energy expenditures and GDP per capita by region

Units: Indexed to 2023



4 SECTORAL ROADMAPS

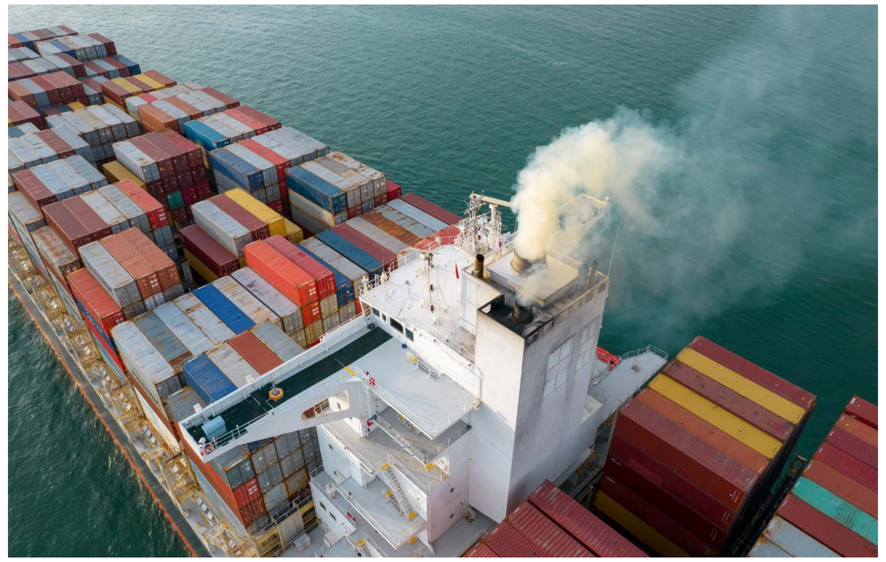
We focus our pathway to net zero (PNZ) on developments within the most energy-intensive industries and the demand and supply sectors responsible for the lion's share of emissions. We have selected nine sectors that together currently contribute more than 29 Gt to global CO_2 emissions, which is over 80% of current global energy-related and industrial process emissions.

In this chapter, we detail the pathways to net zero for these nine chosen sectors on both the demand and supply sides, covering technologies and policies. Some of the sectors which contribute smaller shares to global CO_2 emissions, and which do not form part of our focus in this chapter, include manufactured goods, construction and mining, rail, energy sector own use, and agriculture.

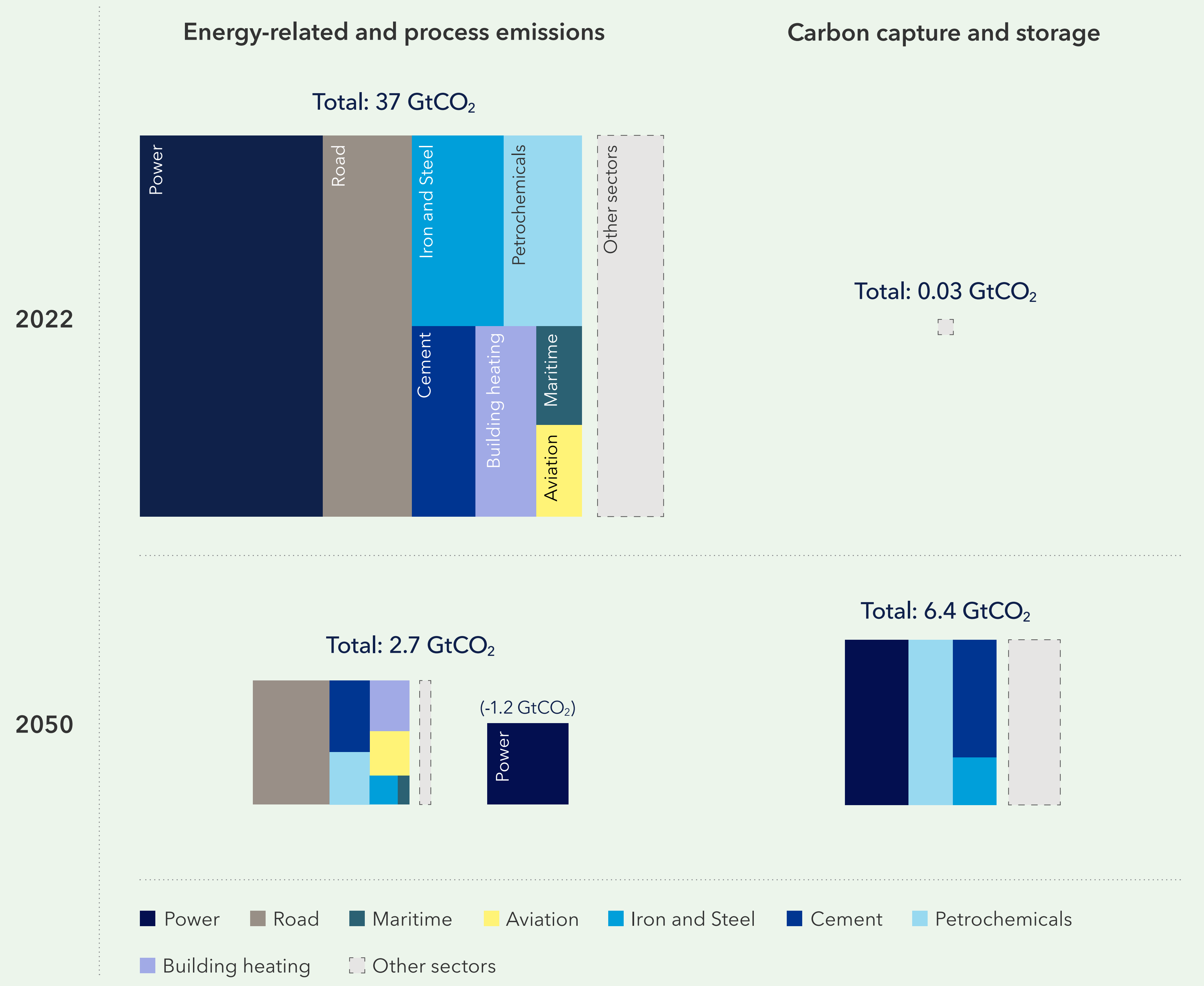
In terms of sectoral contributions, road transport is currently by far the largest emitter among the seven demand-side sectors in focus, with a 40% share of the total. Under the PNZ, the road transport sector, with difficult conditions for CCS, still dominates the remaining emissions, contributing half of the total, with iron and steel in second place.

In the PNZ, the easier-to-abate power sector sees a much more rapid transition towards renewable electricity and a much higher prevalence of CCS in the world's fossil-fuelled plants, as elaborated in the power section, resulting in power reaching net-zero emissions in the early 2040s.

CCS and carbon removal technologies such as DAC are essential to reach net-zero and are described in the dedicated roadmap. For CCS, there is a stark contrast between stationary, large point sources (such as manufacturing and power) where CO_2 emissions at high concentrations can be captured relatively cost-effectively, versus mobile, dispersed sources (such as transport and buildings) where CCS technology cannot be applied due to the low density of emissions. CSS in these latter sources therefore remains near zero within our 2050 timeframe.



Decarbonization is essential in eight sectors



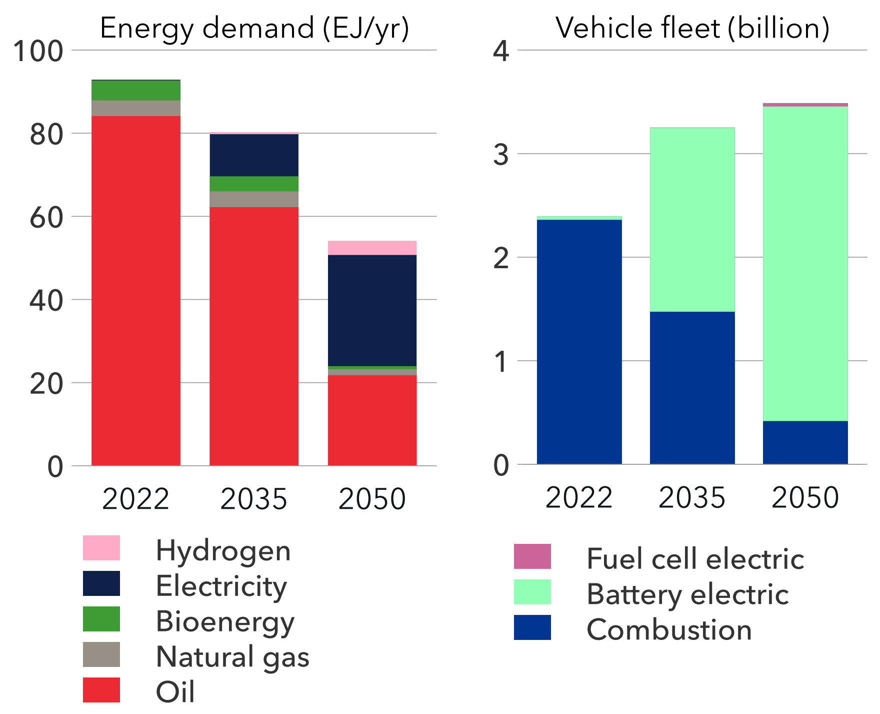
4.1 ROAD

PNZ	42% Decline in energy demand by 2050	74% Decline in oil demand by 2050

Road transport, among the largest GHG emitters today is also difficult to fully abate, with about 2 $GtCO_2$ emissions remaining by 2050. The basic technologies used to achieve the pathway already exist, with the principle means of reducing emissions being electrification, and the replacement of fossil-fuelled ICEs. However, some fossil-fuelled road transport, mostly trucks, will persist, explaining residual oil demand and emissions.

FIGURE 4.2

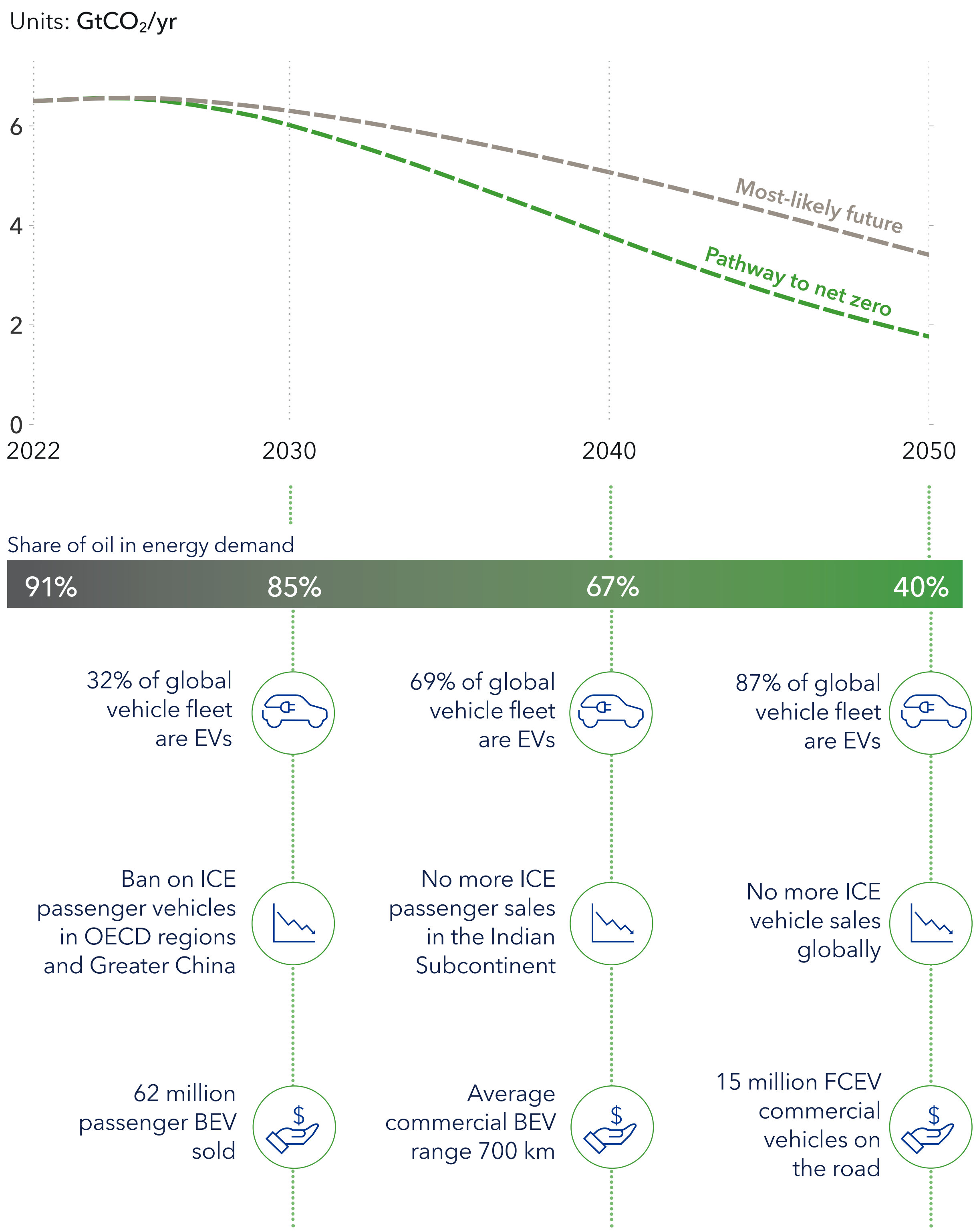
World road transport indicators



SECTORAL PATHWAY		POLICY LEVERS
ACCELERATED EV UPTAKE	Government support to EV purchasers and manufacturers with direct and indirect purchase-price reductions in the next few years, supported by quotas for EV shares in manufacturers' fleets. Fuel-cell electric vehicle (FCEV) technology will only prevail in small shares of long-haul trucking and public transport, whereas the advantages of electric propulsion will edge out both fossil fuel and hydrogen in all segments of road transport.	– Subsidized EV purchase – Reduced toll roads and parking fees to incentivize EV uptake, in addition to other financial and user incentives – Regionally differentiated ICE bans
REDUCED FOSSIL FUEL USE	Some fossil fuel-propelled road transport will remain. New sales of ICE vehicles will eventually be banned in all regions except Sub-Saharan Africa. OECD regions and Greater China have a phased ban on fossil-fuelled passenger vehicles from 2030 onwards, with other regions following. The sales prohibition is extended to commercial vehicles just a few years after passenger ICE vehicle sales are stopped. The PNZ does not rely on a 'cash-for-clunkers' (early retirement) programme.	– Stricter fuel economy standards and emission limits for ICEs – Additional taxes on gasoline and diesel – Fossil-fuel subsidy removal
INFRA-STRUCTURE AND ECOSYSTEM INVESTMENTS	EV uptake is already subsidized in many regions. A decline in fossil-fuel subsidies frees up government budgets for investments in e.g. EV technology and improvement of battery charging speed, followed by improvements in availability and average charging speed of charging stations, and manufacturing capacity and transitioning conventional car manufacturers.	– Public infrastructure investments – R&D battery chemistries – Investment support in manufacturing capacity/ conversion

FIGURE 4.3

World road sector direct CO_2 emissions



4.2 AVIATION

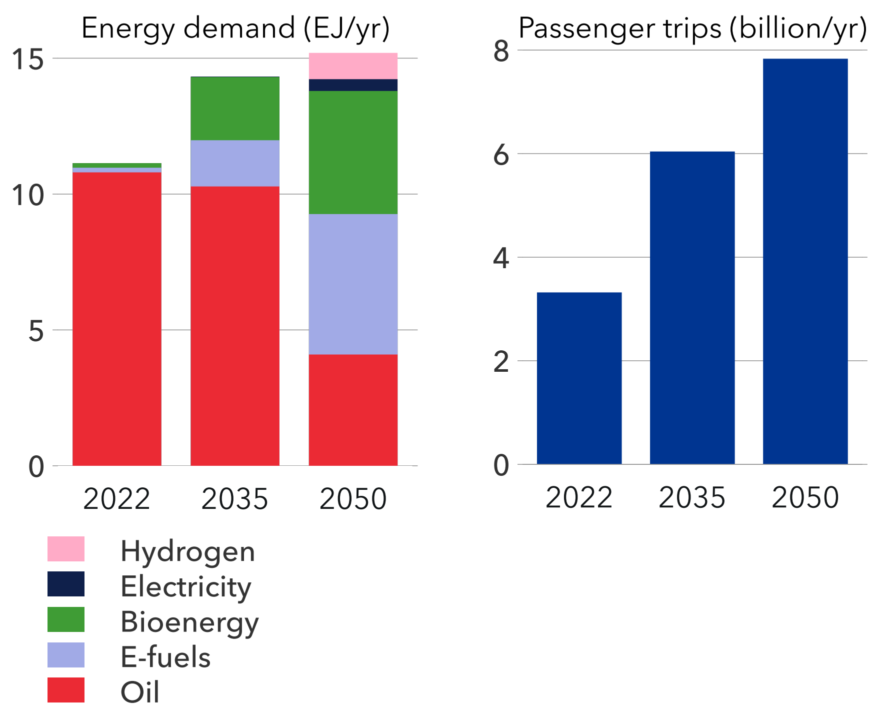
PNZ

60%	27%
Decline in emissions from 2022 to 2050	Share of oil in 2050

Although 25% below our ETO forecast, our PNZ assumes a solid growth in global passenger flights from 3.3 billion in 2022 to 7.8 billion in 2050. Due to the introduction of decarbonized fuels, emissions from aviation decline 60% to 330 $MtCO_2$ per year between 2022 and 2050. Electrification is limited to short-haul flights, with biofuel and hydrogen applicable to medium and long-haul flights.

FIGURE 4.4

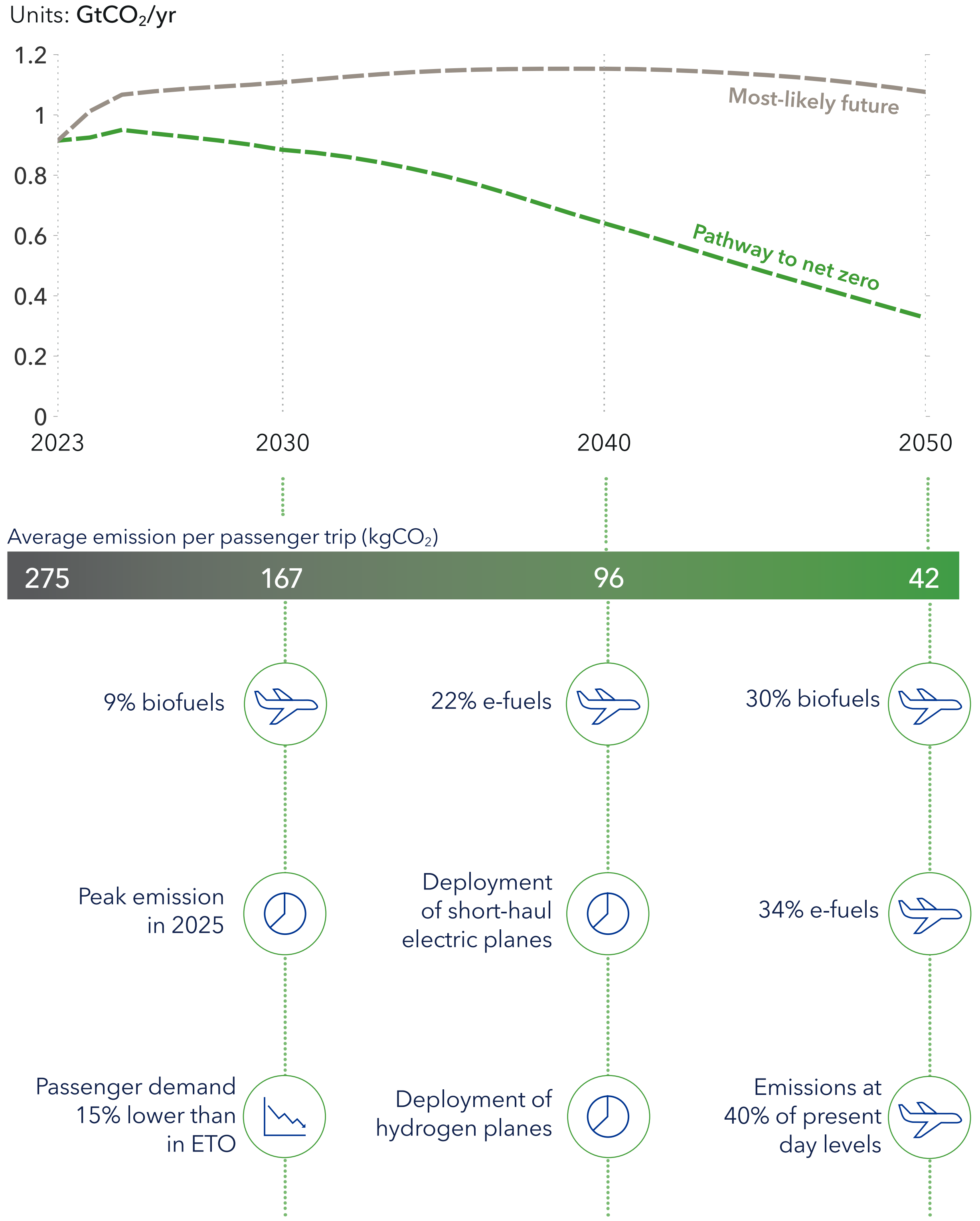
World aviation indicators



SECTORAL PATHWAY		POLICY LEVERS
INCREASED EFFICIENCY	Efficiency will continue to improve due to better engine technology, improved aircraft design, larger planes, and better flightpath logistics.	– Technical requirements on fuel economy and emissions
SUSTAINABLE AVIATION FUEL (SAF)	Fuel blending mandates will be the main policy tool for enforcing uptake of low-carbon fuels in a PNZ future. SAF can replace the existing kerosene with relatively little adjustment of fuel tanks and engines (depending on the blending ratio). SAF is likely to consist mainly of biofuels, particularly hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK). Extensive research into hydrogen has indicated its potential for use in medium-haul aircraft. This is likely to represent more than half of SAF in high-income regions from around 2040.	– Fuel targets and blending mandates – Technology mandates for electric short-haul flights
REDUCED DEMAND	Reducing demand for flying and limiting growth in the number of flights via increased cost. Flying should be perceived as a luxury, and restricting the number of flights per person is a possible auxiliary policy.	– Increasing fees and taxes, and more costly fuels

FIGURE 4.5

World aviation sector direct CO_2 emissions



4.3 MARITIME

PNZ

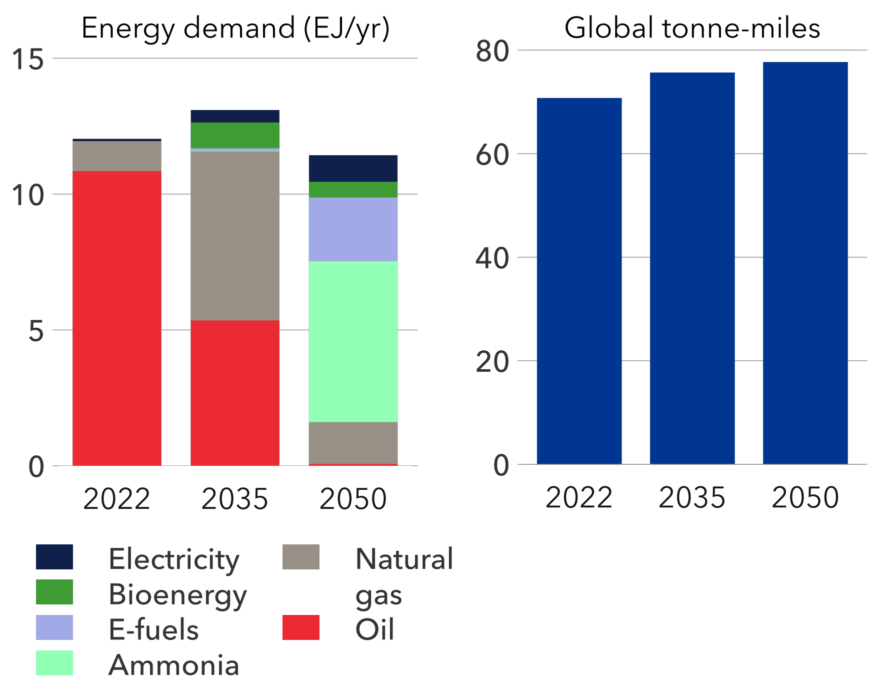
92%
Decline in emissions from 2022 to 2050

<1%
Share of oil in 2050

Decarbonizing shipping by 2050 requires higher energy efficiency and improved logistics. It will also need a very different fuel mix to today's predominance of marine fuel oils. This includes new fuels derived from low-carbon sources, irrespective of energy-efficiency gains. Our PNZ has a diverse future energy mix comprising both fossil and low-carbon fuels, with fossil fuels gradually phased out.

FIGURE 4.6

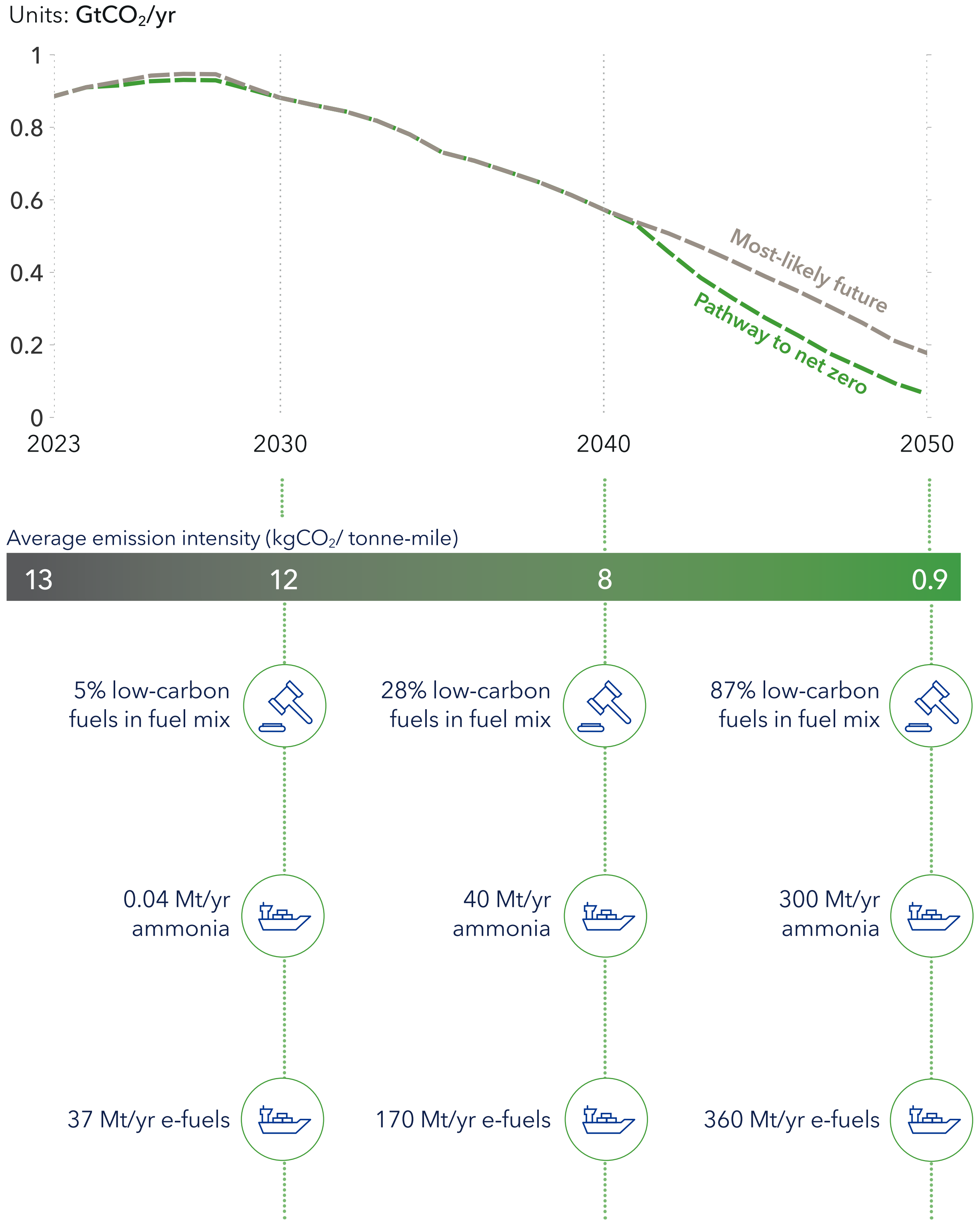
World maritime indicators



SECTORAL PATHWAY		POLICY LEVERS
REGULATIONS AND POLICY	A clear, long-term, and predictable regulatory framework for emission reductions will be the key driver for technology development and investing in deploying carbon-neutral fuels and solutions. Initial policies need to focus on lowering critical barriers such as the cost differential between new and conventional fuels.	– Technical or operational requirements on GHG emissions – Carbon pricing that ensures a level playing field for ships that run on more expensive carbon-neutral fuels – Mandated uptake of low-carbon fuels
ACCESS TO INVESTORS AND CAPITAL	The energy transition in shipping will require major investment in infrastructure and production capacity for supply of carbon-neutral fuels. The onshore investment costs and the higher cost of producing zero-carbon or carbon-neutral fuels will lead to significantly higher fuel costs for ships.	– Investment support to infrastructure related to production, distribution and refuelling of carbon-neutral fuels
CARGO OWNER AND CONSUMER EXPECTATIONS	In light of fuel-switching ambitions, it is vital to ensure that demand for low- and zero-carbon fuels can be met. This is also partially influenced by governmental strategies and policies.	– Reduce obstacles to implementation of carbon-neutral fuels, such as technical and organizational barriers

FIGURE 4.7

World maritime sector direct CO_2 emissions



4.4 BUILDINGS HEATING

PNZ

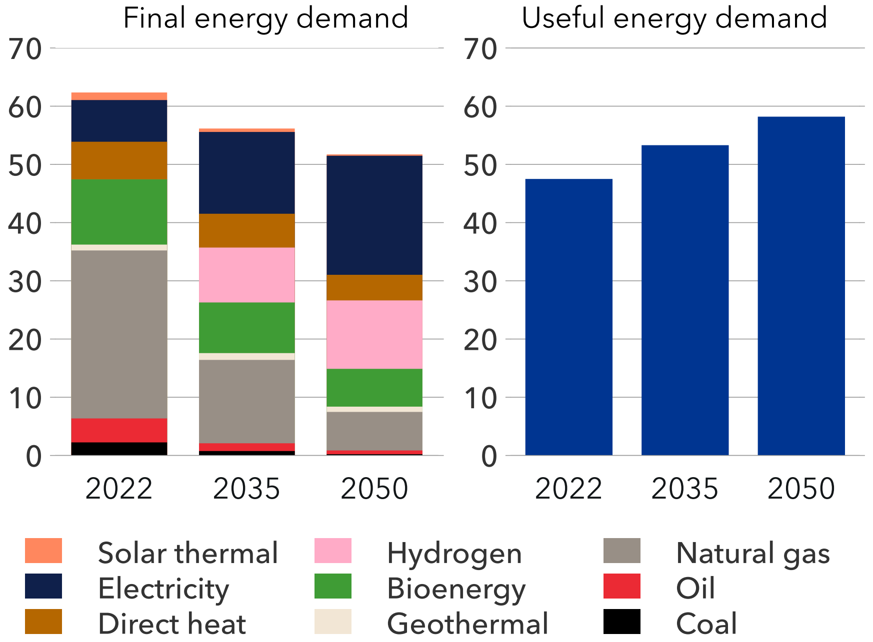
84%	**1.3** $GtCO_2$
Decline in emissions from 2022 to 2050	Gap with ETO forecast in 2050

A drastic reduction in total CO_2 emissions in our pathway is primarily achieved through electrification and energy efficiency. The technology for net-zero emissions from heating buildings already exists; the challenge lies in the speed and efficiency of its implementation. By 2050, electricity (40%), driven by heat pump uptake, and hydrogen (23%), used in gas or dedicated boilers, dominate buildings heating demand.

FIGURE 4.8

World buildings heating indicators

Units: EJ/yr

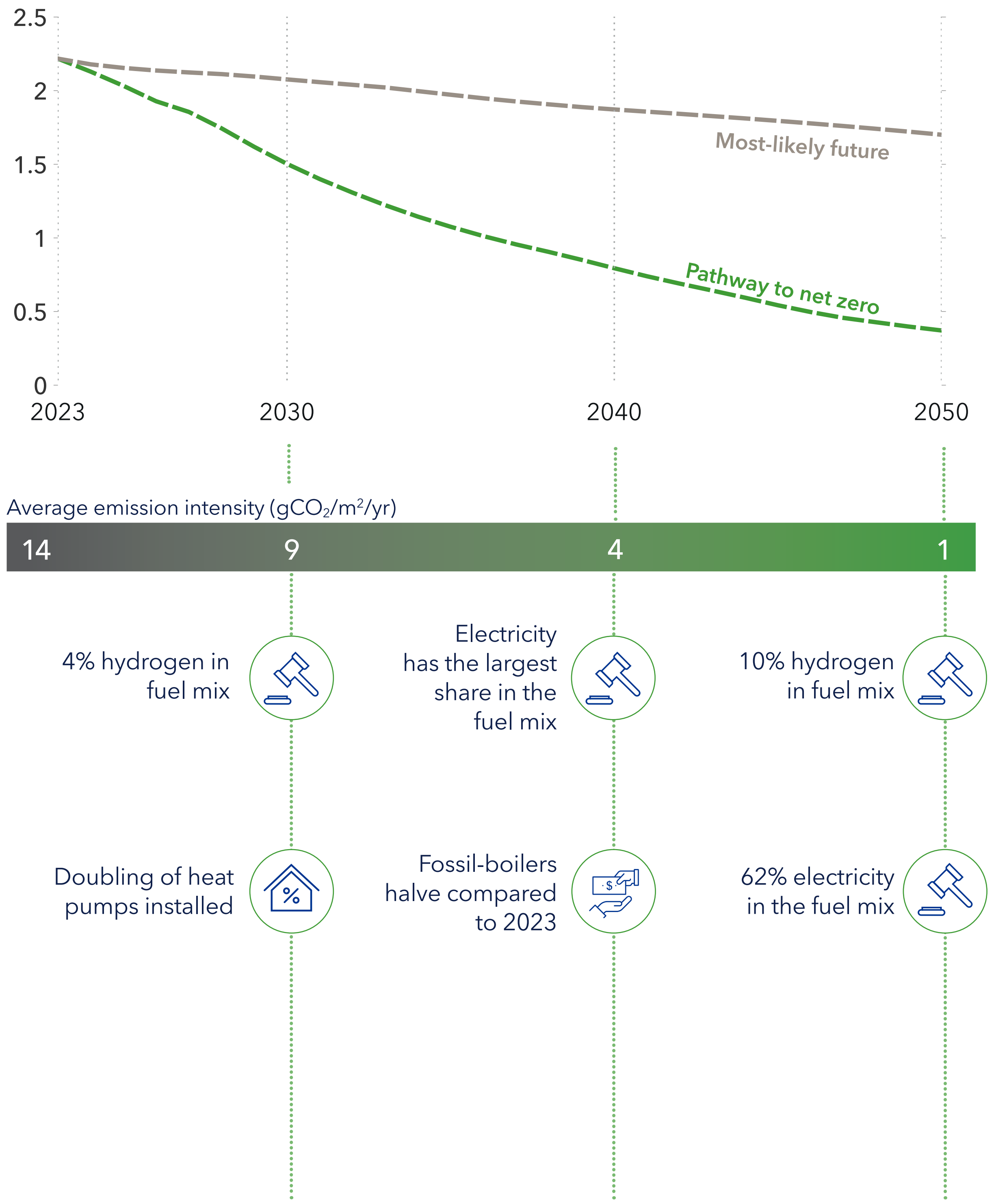


SECTORAL PATHWAY		POLICY LEVERS
PHASE-OUT FOSSIL-FUEL EQUIPMENT ACCELERATE ELECTRI-FICATION	Partial ban on fossil-based heating equipment, and mandated electricity-ready new buildings, translating to a limited and regionally differentiated percentage of new buildings allowed to use fossil fuels. This leads to a faster phase-out of fossil-fuel equipment and quicker electrification. New fossil-based equipment also has limited lifetime, thus leading to faster replacement with electricity or hydrogen-based heating.	– Regulations and partial bans limiting equipment choices for fossil-fuel based heating
HIGHER COST OF CAPITAL FOR FOSSIL-FUEL EQUIPMENT	The 'stranded risk' of fossil-fuel infrastructure in buildings significantly reduces the attractiveness of fossil-fuel heating equipment, and curtails the ability to garner debt or capital equity to install them in new commercial buildings. Today, oil and natural gas boilers have a cost of capital of 17%, which increases to 20% in 2050, compared to the 7% cost of capital of electrical equipment in 2022.	– Higher cost of capital on fossil-fuel boilers in commercial buildings – Support for technological leapfrogging in selected regions – Consumer-side fossil-fuel subsidy removal
INCREASE ENERGY EFFICIENCY OF BUILDINGS	Higher energy-efficiency standards for existing and new builds leading to lower specific heating demand per floor area unit. Energy efficiency can also be achieved by using innovative building materials.	– Efficiency standards and regulations on building envelope thermal characteristics

FIGURE 4.9

World space and water heating direct CO_2 emissions

Units: $GtCO_2$/yr



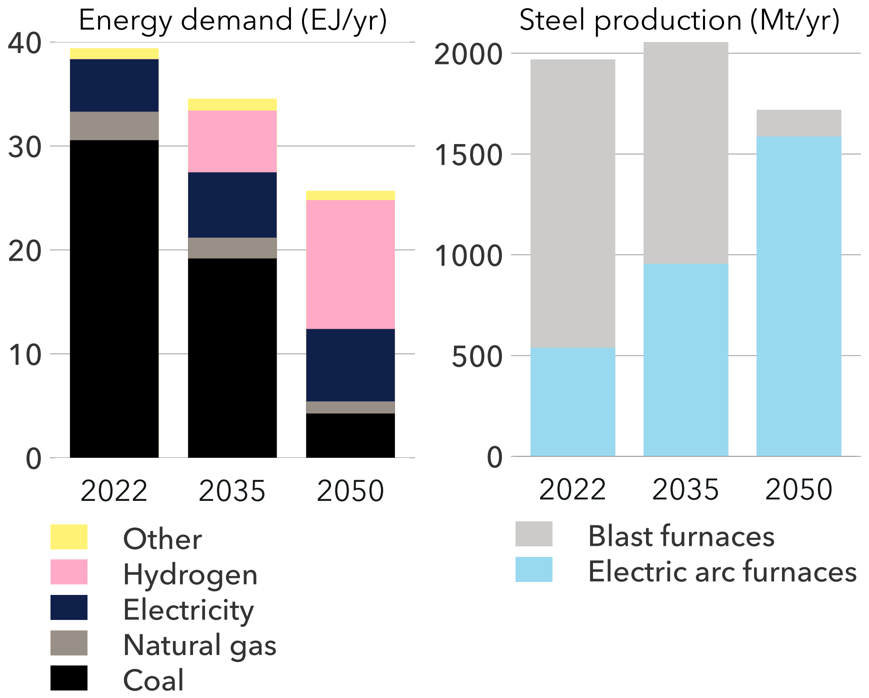
4.5 IRON AND STEEL

PNZ		
	10% Current share of global emissions	**1.9** $GtCO_2$ Gap with most-likely future

Many technologies for our PNZ – e.g. grids, wind turbines, and CCS equipment – need large amounts of steel, but steel production is currently emission-intensive due to heavy coal use. In our PNZ, material efficiency and recycling measures sees a steady reduction in steel use. By 2050, most steel will come from scrap or direct reduced iron (DRI) in electric arc furnaces (EAF), driving emissions down by 94%.

FIGURE 4.10

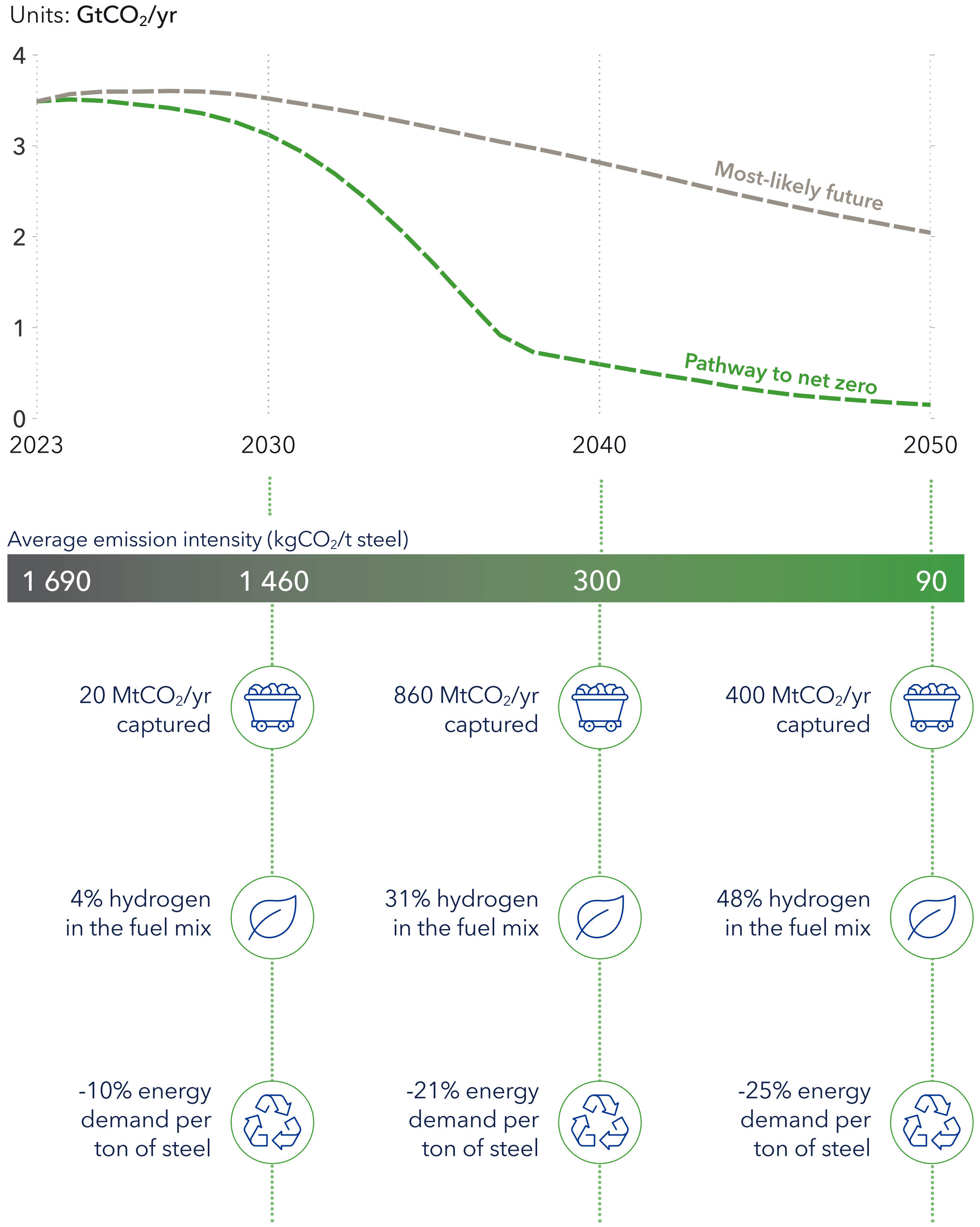
World iron and steel sector indicators



SECTORAL PATHWAY		POLICY LEVERS
DECARBONIZE BLAST FURNACES	Around 40% of energy demand in iron and steelmaking comes from the reduction of iron ore, a process that currently relies predominantly on coal used in blast furnaces. Major barriers to lowering emissions include: the high share of coal in the sector's energy inputs; the long lifetime of incumbent assets; and the typically low margins in a mature, competitive, and commoditized market.	– Carbon price is the most important policy for the commercialization and scaling up of low-carbon iron and steel production.
LOW-CARBON DRI-EAF	Low-carbon steel technologies include the already widely used scrap-based EAF for steel production and the promising direct reduction method. The latter involves the solid-state reduction of iron oxide into iron, where pre-heated iron ore is converted into DRI with hydrogen acting as the reducing agent and energy source. The DRI can then be fed directly into an EAF to produce steel. Low-carbon direct reduction can be either hydrogen-based or natural gas-based with CCS. These two similar technologies are currently either not economically viable due to the high costs and/or low availability of feedstock (e.g. in the case of green hydrogen-based DRI). The direct reduction can also be designed to operate with methane, hydrogen, or a mixture of these gases as the reducing agents. Therefore, blending hydrogen into natural gas is seen as a transition strategy before there is technological readiness for pure hydrogen use.	– Favourable energy taxation for hydrogen production – Support for new DRI-EAF plants – Support for scaling up CCS technologies for natural gas-based DRI.
IMPROVE MATERIAL EFFICIENCY AND RECYCLING	Steel is virtually 100% recyclable, and improving the collection and recycling of scrap steel in EAF is essential. In our PNZ, by 2050, all steel production in the OECD and 90% of production in other regions is assumed to be via EAF, with a global steel recycling rate of 95%. There is also a decrease in the steel intensity of new buildings (20% lower by 2050) and a faster improvement (1.2% per year compared with 1% per year in the ETO forecast) of energy intensity in steel production itself.	– Recycling policy enables a faster transition to steel production via EAF. – Mandates in construction standards

FIGURE 4.11

World iron and steel sector direct CO_2 emissions



4.6 CEMENT

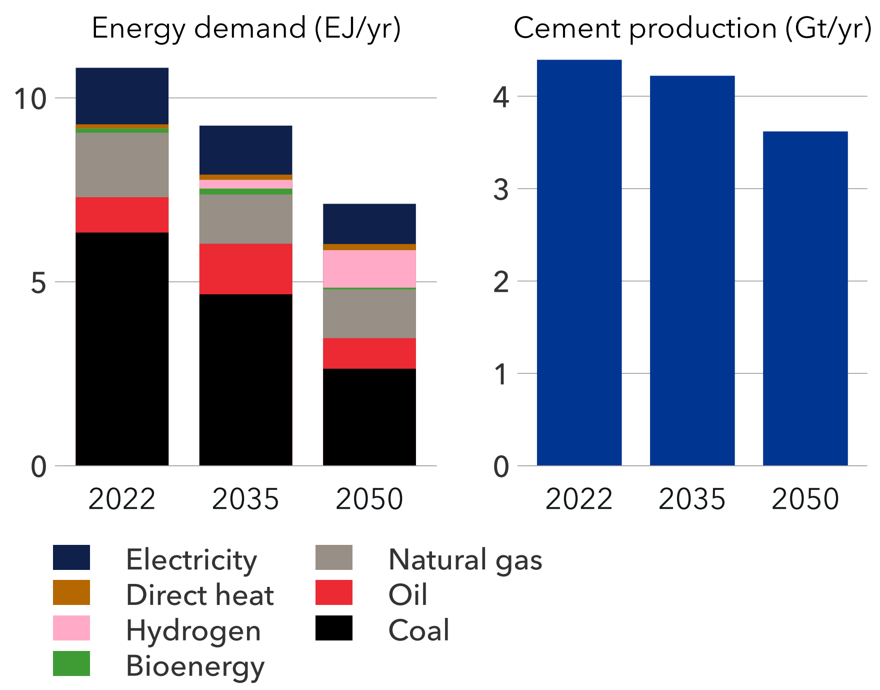
PNZ

7%
Current share of global emissions

1.8 $GtCO_2$
Gap with most-likely future

Although controversial and energy-intensive, cement's unique properties make it unlikely to be replaced in the coming decades, even in our pathway to net zero. Massive deployment of CCS and changes to cement formulations will be required in a PNZ future to decrease the annual CO_2 emissions from 2.4 Gt today to 0.5 Gt in 2050.

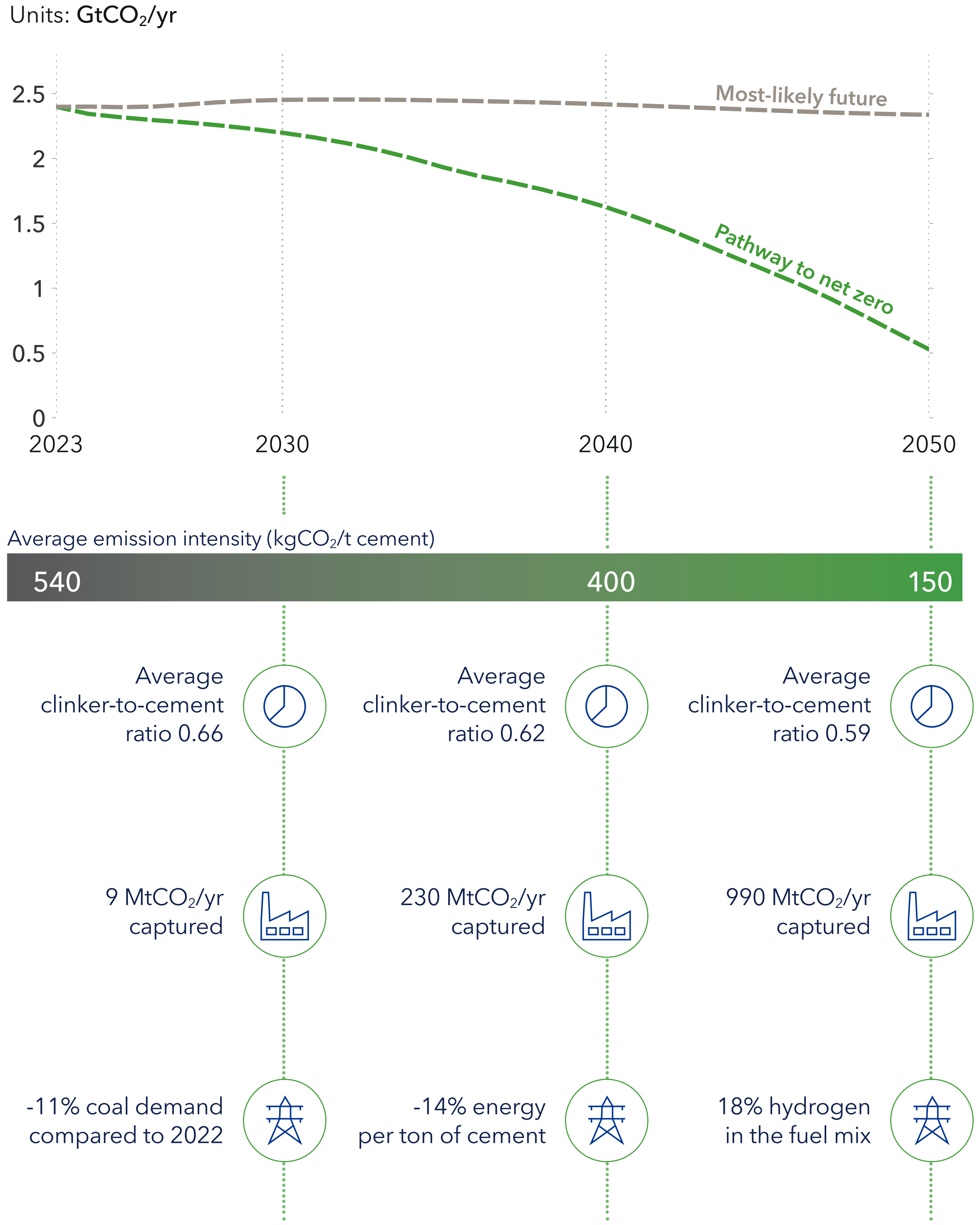
FIGURE 4.12
World cement sector indicators



SECTORAL PATHWAY

SECTORAL PATHWAY		POLICY LEVERS
REDUCED DEMAND	Reduced demand via the combined effect of policies and decarbonization costs that are passed on to the consumers and make cement less competitive. Enforcement of public procurement for low-carbon cement is also important.	– Regulation and government promotion support to new or alternative materials
LOWERING CLINKER-TO-CEMENT RATIO	Reducing the clinker to cement ratio is achieved by using clinker substitutes and enhancing the strength of the clinker by using additives, alternative binders, etc.	– Low-carbon cement procurement – Easing regulation on cement composition
CARBON CAPTURE	Carbon Capture, Utilization, and Storage (CCUS) is the main and most effective abatement solution because of unavoidable process emissions, and will capture 76% of direct emissions by 2050. The technology remains in an early phase of deployment, however, with only a handful of projects being announced so far.	– Carbon price and investment support
ENERGY EFFICIENCY AND FUEL MIX	Improvements in energy efficiency of clinker production lead to reductions in both direct and indirect CO_2 emissions. Using alternatives to fossil fuels is challenging given compatibility limitations. Coal remains the main heat source for clinker production, though hydrogen has an important role. Waste co-processing (plastics, tyres, etc.) also represents a significant share, as it diverts waste from landfills or incineration, and is a source of income for the industry.	– Efficiency standards – Increased taxation on fossil fuels triggers fuel switching, and boosts use of alternative fuels.

FIGURE 4.13
World cement sector direct CO_2 emissions



4.7 PETROCHEMICALS

PNZ

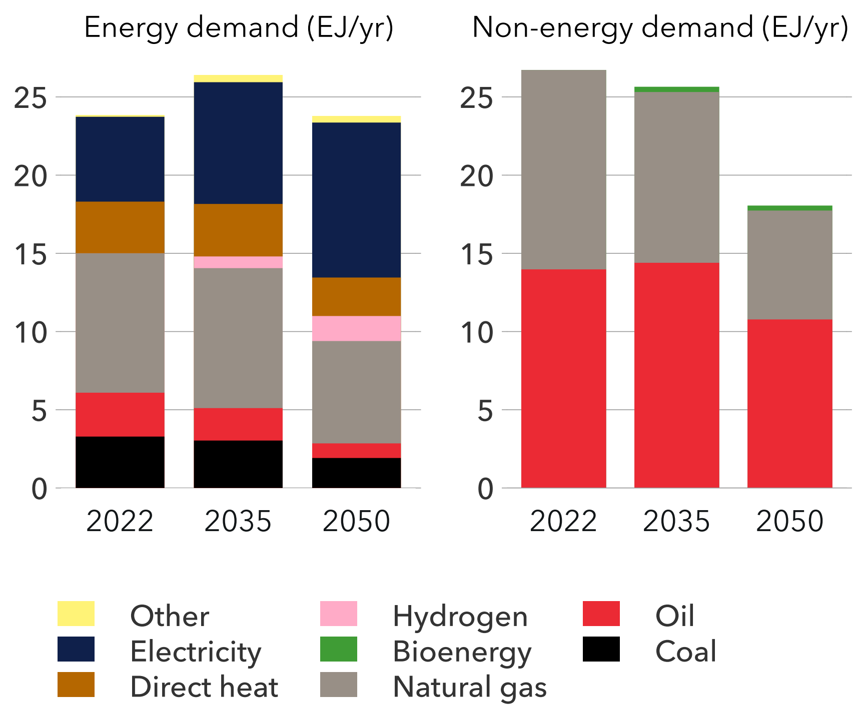
9% Current share of global emissions

1.1 $GtCO_2$ Gap with most-likely future

The chemicals and petrochemicals industry makes many of the chemical building blocks for products widely used in our everyday lives: plastic packaging, fertilizers, pharmaceuticals, tyres, and so on. Manufacturing these products, which also rely on fossil fuels as feedstock, will remain a key driver of oil and gas demand. The diversity of processes implies that a broad range of solutions are needed.

FIGURE 4.14

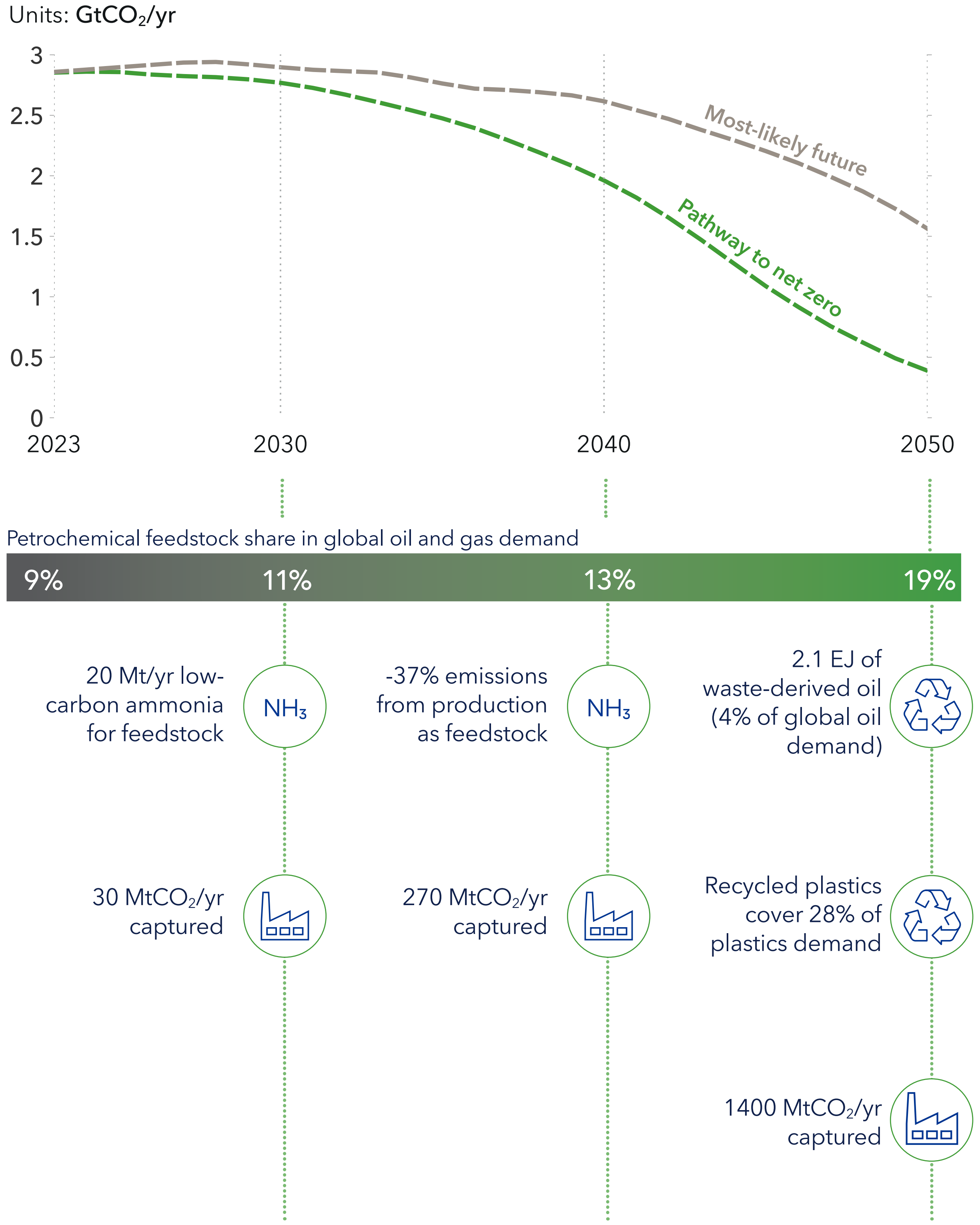
World petrochemicals sector indicators



SECTORAL PATHWAY		POLICY LEVERS
REDUCED PLASTICS DEMAND	Plastics production represents a third of the sector's energy demand, and increased recycling rates will help lower the energy demand. Eco-design of consumer products, with an increased focus on product recyclability, will have to follow. This also includes a decrease in plastic waste in the manufacturing process. Mechanical recycling has limitations, and most improvements for non-recyclable polymers can be achieved through waste-to-energy (including co-processing) and waste-to-fuel technologies for better use of the embedded energy. Indeed, for plastics, around half the carbon is embedded into the material itself and is not accounted for in the direct emissions of the sector. Therefore, the disposal phase has a strong impact on the final carbon footprint.	– Landfill bans for plastics, avoiding long-term GHG emissions, and promoting use of non-recyclable plastics as a source for alternative fuels. – Mandated recycling, with a generalization of extended producer responsibility regulations on product design for higher recyclability – Taxes on unrecycled plastics – Reduction and substi-tution of the demand via measures like banning substitutable single-use plastics will also impact global emissions.
NH_3 LOW-CARBON AMMONIA	Although ammonia production is decarbonized, final use of its derivatives, and their subsequent decomposition in soil, are sources of CO_2 and nitrous oxide emissions. Emissions from producing this key building block of nitrogen fertilizers are currently around 500 $MtCO_2$ per year and must be addressed while also ensuring the security of the food supply. This will thus remain one of the main concerns for governments.	– Support to low-carbon hydrogen, an essential chemical for making ammonia. – Stringent regulation of local nitrate pollution, and interventions on food waste, reduce ammonia derivatives demand.
CARBON CAPTURE	For some processes, such as ammonia production from natural gas, carbon capture has a clear benefit because of the further need for CO_2, often in the same plant. Carbon capture is also cost-effective in that case because of the pure CO_2 output, and several industrial plants already have the technology in place, explaining the rapid future ramp-up	– Carbon price and investment support

FIGURE 4.15

World petrochemical sector direct CO_2 emissions



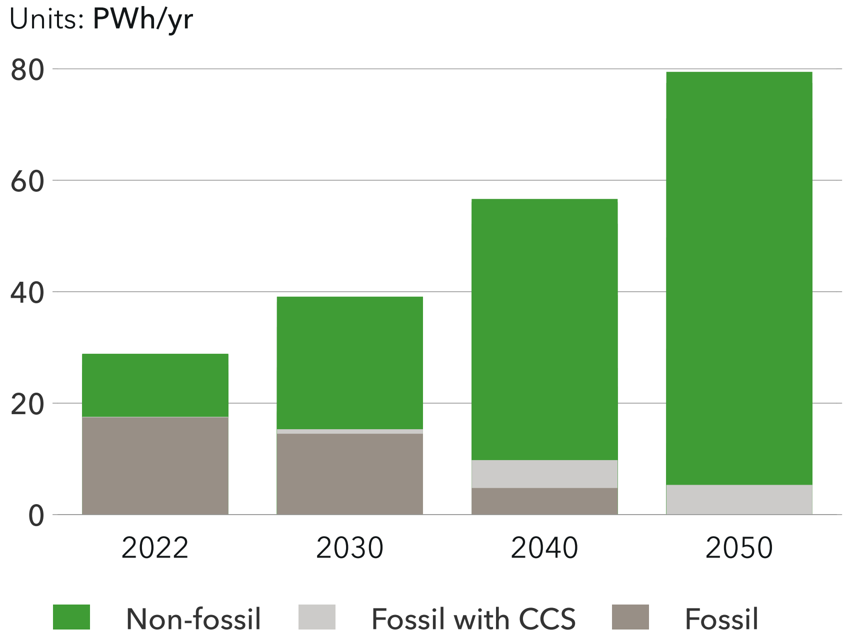
4.8 POWER

PNZ	**7,500 GW** Solar and wind capacity by 2030	**91%** Reduction in CO_2 emissions from 2022 to 2040

Decarbonizing the power sector early and aggressively is crucial for net zero as this sector is currently responsible for a third of energy-related emissions and drives decarbonization in other sectors, such as heating and transport. However, renewables, supported by abated gas power plants and BECCS, will see the power sector has negative emissions from 2043 onwards. Coal-fired plants are also phased-out in the late 2040s.

FIGURE 4.16

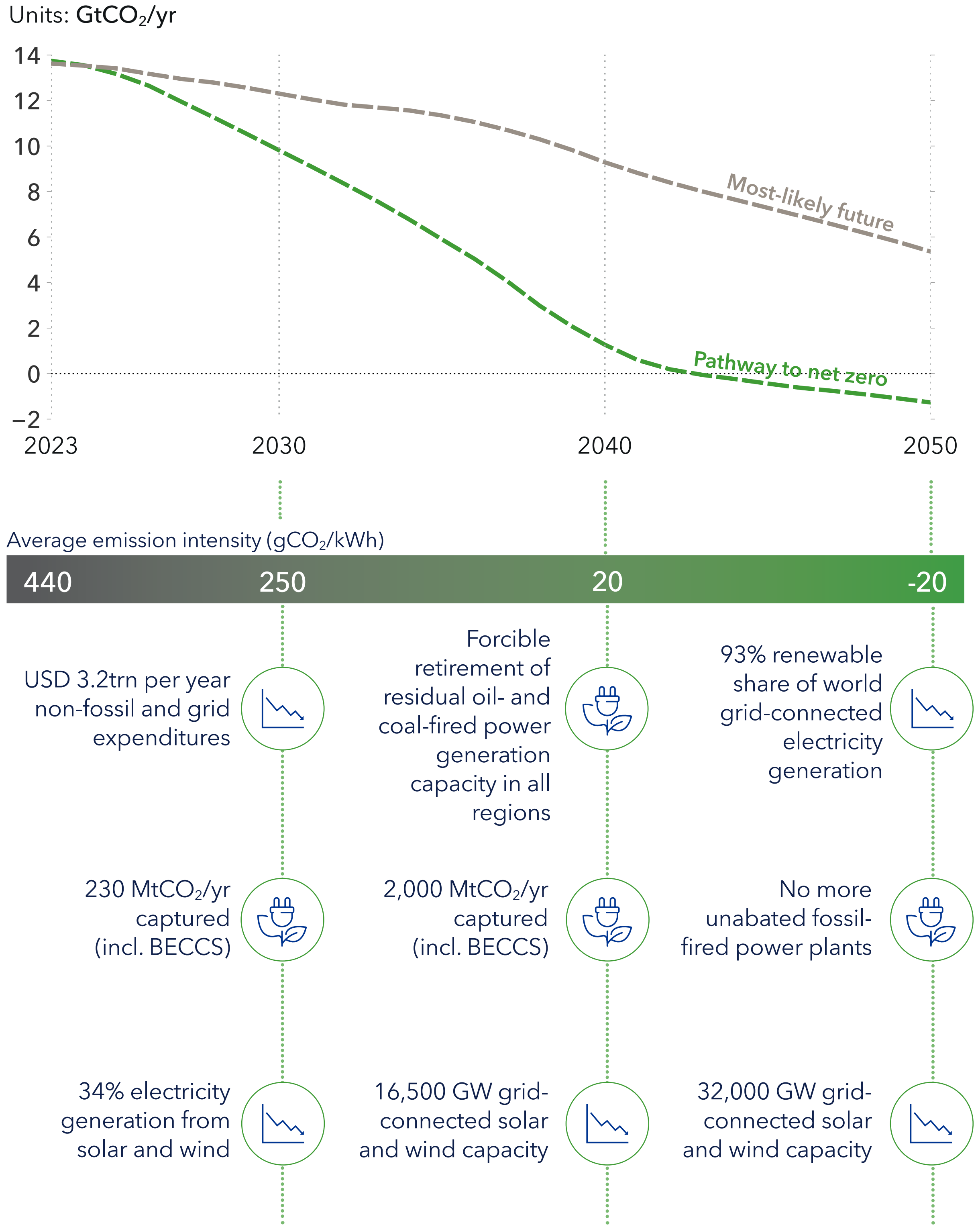
World grid-connected electricity generation



SECTORAL PATHWAY		POLICY LEVERS
DECARBONIZE FOSSIL-FUEL POWER STATIONS	Focusing new investments exclusively on low-carbon power will not decarbonize the electricity mix quickly enough. Thus, a PNZ future also requires investments for decarbonizing existing power generation capacities. CCS is critical to eliminate emissions from the remaining fossil-fuel power plants, especially combined-heat-and-power (CHP) and heat-only power stations. The only renewable alternatives to heat generation are hydrogen, biomass, and waste. In our PNZ, new fossil-fuel capacity additions from 2022 have reduced lifetime mandates by policy, affecting all three types of fossil-fuel power plants, whose lifetimes are reduced from 40 to 25 years.	– Higher cost of capital for investments for fossil-fuel power plants – Combination of fuel transition and CCS to decarbonize heat supply – Residual oil-fired and coal-fired power generation capacity is forcibly retired in all regions from 2045 – Increased carbon prices
INCREASE NON-FOSSIL CAPACITY	Despite its high cost and waste issues, nuclear power still provides carbon-free electricity and has a role in our PNZ. The lifetime of new nuclear power plants is increased from 75 to 100 years. While raising equity financing will be increasingly difficult for fossil-fuel power plants, renewable power investments have a reduced cost of capital, from 7% in 2022 to 6%, in 2025 and thereafter.	– Extension of lifetime of nuclear power plants by delaying the decommissioning of existing nuclear plants and components – Reduced cost of capital for renewable power investments
FLEXIBILITY AND SECURITY	A frequently voiced concern today is that an increasing share of variable renewable energy sources (VRES) in the power system could cause grid instability. This can be relieved by a combination of digital grid infrastructure solutions, battery storage, and backup dispatchable capacity. Key flexibility providers to balance hourly and daily fluctuations include pumped hydro, battery storage, dispatchable generation, demand-side response, and interconnections.	– Increased subsidies to investment for storage capacities connected to VRES – Higher investment in grids
SUPPORT AND MARKET DESIGN	With high shares of solar and wind in power systems, electricity prices will become increasingly volatile, with extended periods of very low or negative pricing if electricity markets continue like today.	– New market design – Financial support mechanisms to keep capture prices above costs to help sustain continued power investments

FIGURE 4.17

World power generation CO_2 emissions



4.9 HYDROGEN

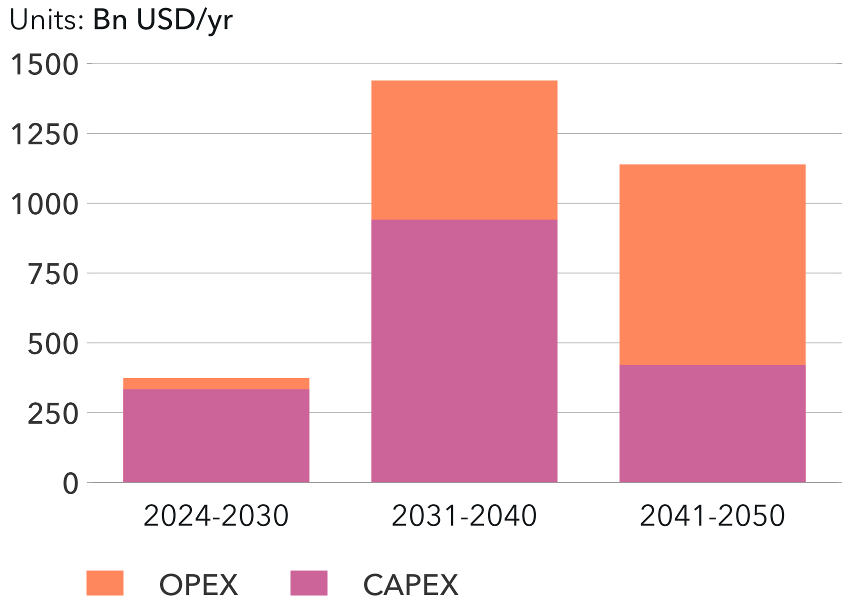
PNZ

12%
Share in energy demand by 2050

USD 330bn
Average global annual investment for 2024-2030

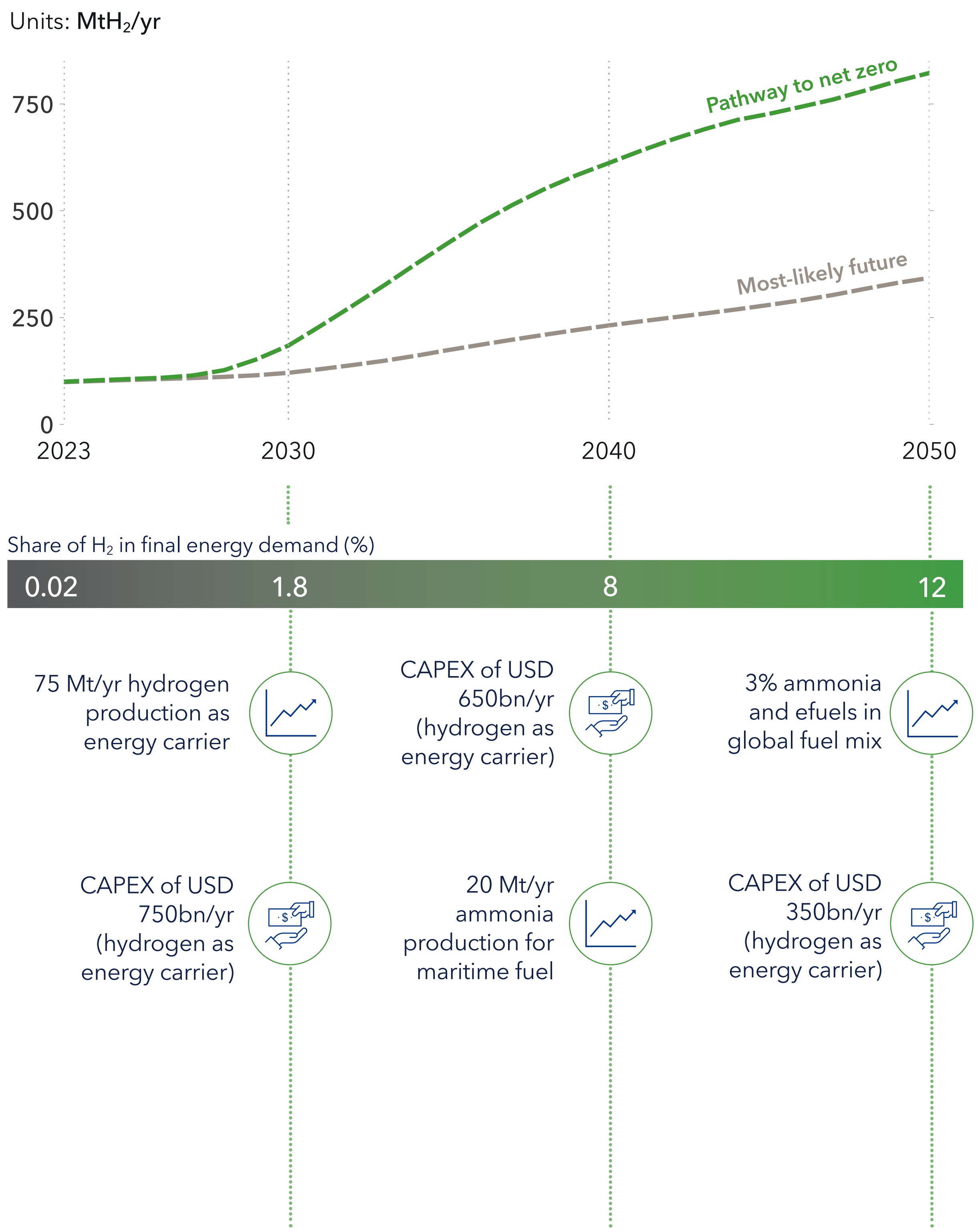
In our PNZ, hydrogen's share in final energy demand jumps from 0.02% in 2022 to 12% in 2050 (15% if including hydrogen derivatives). Hydrogen is integral to net-zero strategies being developed by many countries and is urgently needed to decarbonize hard-to-abate sectors. The scale of hydrogen demand in our PNZ implies a substantial inter-regional trade via ships and pipelines, for which the basic technologies already exist.

FIGURE 4.18
Global annual average expenditure for production of hydrogen as energy carrier



SECTORAL PATHWAY		POLICY LEVERS
INCREASE HYDROGEN DEMAND	Support, incentives, and mandates to create hydrogen demand, especially in some hard-to abate sectors like aviation, iron and steel production, and high-heat processes.	– Energy taxation to favour hydrogen – Mandates on fuel-mix shifts and emission trajectories – Requirements for refineries to raise the share of hydrogen in their energy mix
CAPEX REDUCTION	CAPEX-reducing measures on the production side to boost cost learning curve-based cost reductions for hydrogen. Support mechanisms will be strongest in lower-income and OECD regions.	– CAPEX support to integrated renewable electricity and electrolyser projects – Subsidies to grid-powered, renewables-based projects – Support for steel production to shift to hydrogen
RESEARCH AND DEVELOPMENT	Ongoing R&D efforts must aim to improve polymer electrolyte membrane (PEM) fuel cells and electrolysers, as well as storage and transport options through improved tank design and metal hydrides.	– Decrease cost of hydrogen technologies – Research incentives

FIGURE 4.19
World hydrogen production



4.10 CCS AND DAC

PNZ

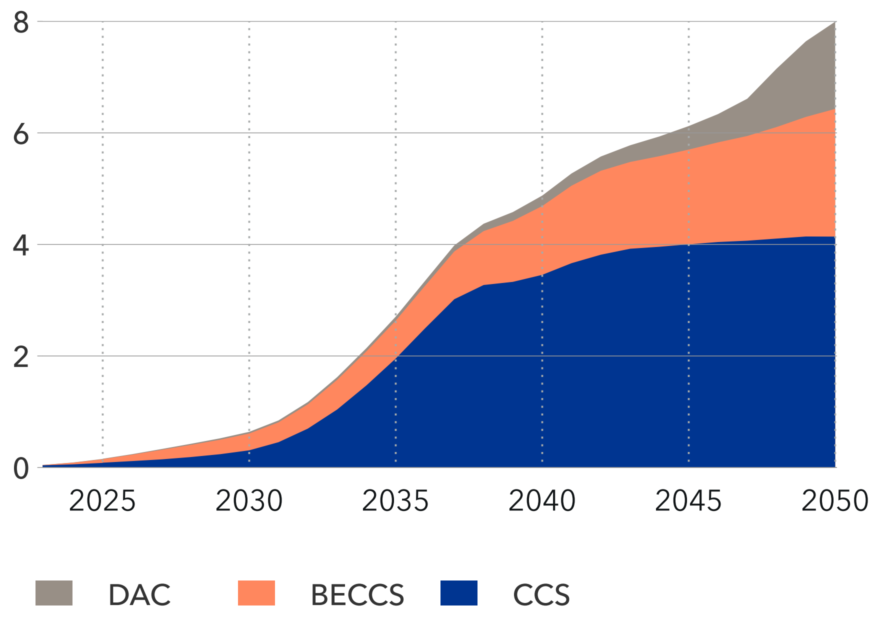
45% Share of total CO_2 emissions captured in 2050

8 $GtCO_2$ Total captured (CCS & DAC) in 2050

Reaching net zero is virtually impossible without CCS for sources like cement processing and gas peaker plants that are infeasible to replace. In addition, DAC allows removal of emissions directly from the atmosphere. Today, CCS captures just 0.1% of total CO_2 emissions, but this is expected to increase to 45% (of profoundly lower emissions) in 2050. Costs limit the deployment of both CCS and DAC facilities.

FIGURE 4.20

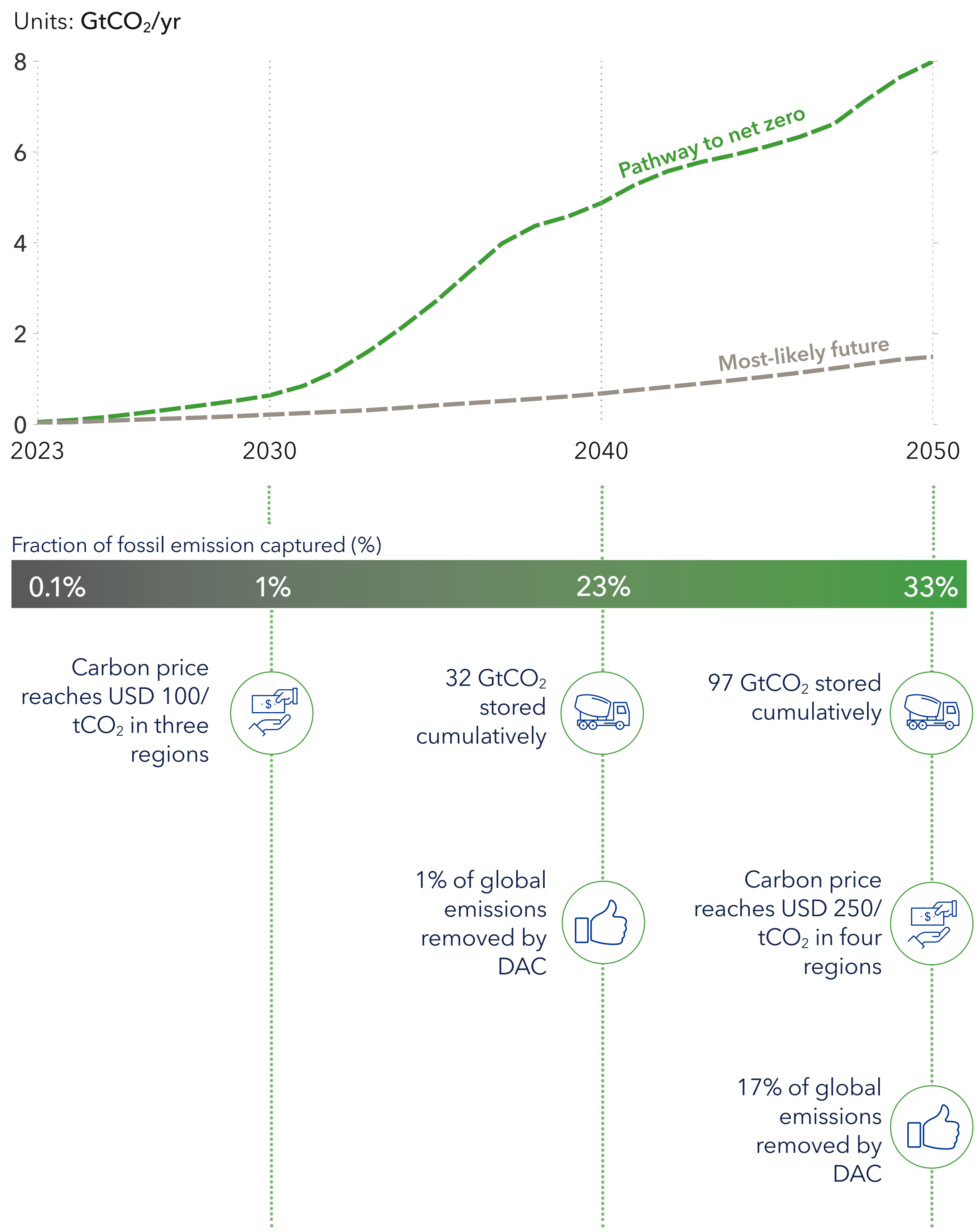
Total CO_2 emissions captured by CCS, BECCS, and DAC



SECTORAL PATHWAY		POLICY LEVERS
INFRA-STRUCTURE	Infrastructure to transport and store CO_2 safely and reliably is essential for CCS expansion worldwide. IEA's analysis of CO_2 emissions from power and industrial facilities in China, Europe, and the US finds that 70% of emissions are within 100 km of potential storage (IEA, 2021b).	– Infrastructure support enabling shorter transport distances between emissions and storage
REDUCE COST	Cost is the main inhibitor of CCS deployment. Industries weigh the prohibitive cost of CCS against relatively inexpensive – in some regions non-existent – carbon prices.	– Higher carbon prices incentivizing deployment – Government support and subsidies. Expected to be driven particularly by high GDP regions – Incentives per tCO_2 captured
INCREASE INSTALLED CAPACITY	The combined capacity of commercial CCS facilities operating today is nowhere near enough to move towards net-zero emissions. Without a major ramp-up, achieving net-zero emissions by mid-century will be impossible.	– CAPEX/OPEX support and policies promoting value-chain and infra-structure development
GOVERNMENT SUPPORT FOR DAC	Our PNZ sees DAC as a necessary compliment to CCS because of the unavoidable emissions that will remain in 2050, particularly from lower-income regions. Government support and subsidies can make DAC competitive as a carbon-offset method over time by progressing the industry's cost-learning curves. By sponsoring DAC, higher-income regions can enable net zero by mid-century, even if lower-income regions have still not reached net zero nationally.	– CAPEX/OPEX support and policies promoting ramp-up of DAC capacity.

FIGURE 4.21

Emissions captured with CCS and DAC



5 REGIONAL ROADMAPS

In our *Pathway to Net-Zero Emissions* (PNZ), we emphasize that the ten regions will move at different paces to reach net zero. Different regional dynamics result in varying emissions trajectories, where GDP per capita is the main driving force.

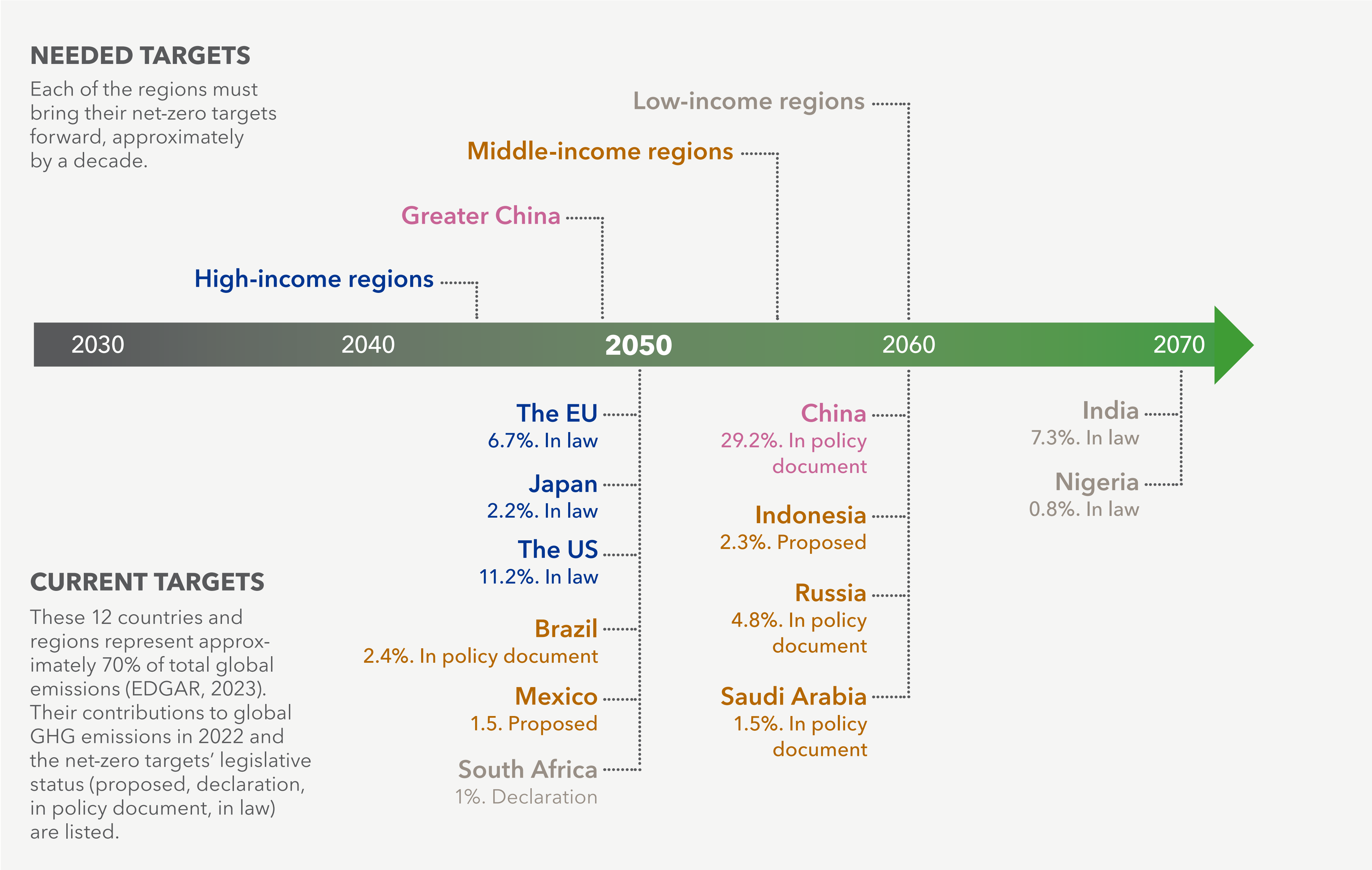
Our vision for distinct regional transitions
The primary objective of our PNZ is to reach net-zero emissions by 2050 to limit the impact of climate change. The PNZ plays out in the context of a near-doubling of global GDP between now and 2050 along with a rise in the global population to 9.6 billion people (with both parameters in line with mainstream projections). In our PNZ, GDP per capita is the main driving force for emissions trajectories to 2050.

Where our PNZ differs from our main *Energy Transition Outlook* forecast is in the speed of both the transition to non-fossil energy sources and the uptake of carbon removal technologies. In our pathway, high-income regions need to fast-track their energy transitions such that they achieve net zero before 2050; middle-income and with low-income regions following as fast as possible before 2060, depending on their capacity and potential for faster decarbonization.

Requiring high-income regions to transition considerably faster than elsewhere frontloads some of the transition costs onto those regions because the scaling up of their transitions creates an automatic decrease in the unit costs of renewables, storage, grid, and carbon removal technologies through accelerated R&D and other volume-based cost learning effects. This lowers technology costs for follower regions and makes their transitions more economically and politically feasible. While this trajectory is in keeping with the UNFCCC's principle of common but differentiated responsibilities between nations, it does not fully address climate justice concerns (Macquarie, 2022) which recognize that those populations most affected by climate damage are generally those who have contributed least to cumulative energy-related emissions. Addressing climate justice includes, but is not limited to, mobilizing climate finance from high- to low-income countries, but is not directly addressed by our analysis and pathway.

In the context of achieving net zero, time is of the essence. In other words, immediate decarbonization action must not be delayed until consensus on climate justice is achieved or debates are settled on the optimal technology mix for net zero. Instead, the assumption behind our pathway is that there is immediate and pragmatic action to address obvious obstacles to the achievement of net-zero emissions in the next 27 years, including the rapid removal of coal from the energy mix, scaling up renewables and hydrogen, and addressing critical bottlenecks like land use, permitting, and infrastructure.

Against this backdrop, we recognize that countries should tailor their transition according to their own context. PNZ opportunities and challenges will vary between and within countries, and the sections that follow are therefore necessary regional generalizations based on current energy, emissions, and GDP situations.



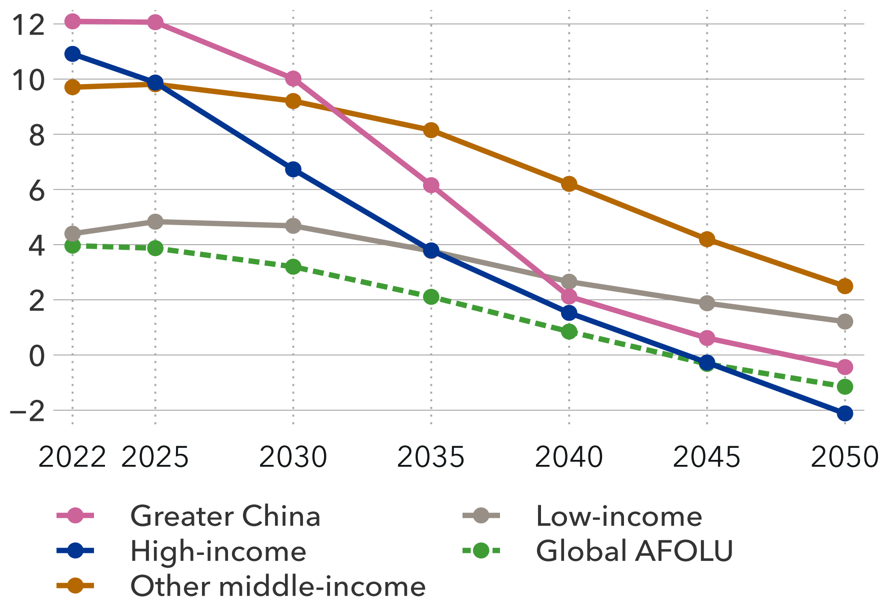
Different region dynamics

All countries and regions have different starting points regarding resource and finance availability, energy sector infrastructure, workforce qualifications, and human development. In our PNZ, we emphasize that the ten regions will take different paths towards their net-zero destinations. However, there are sufficient similarities for us to classify the regions into groupings on the basis of the pace at which they can reach their emissions trajectories. It is expected that high-income regions will reach net zero faster and do more (before 2050) than middle- and low-income regions, as shown in Figure 5.1. Each of the three groups have some common opportunities and challenges which will surface on the pathway to net zero.

FIGURE 5.1

Pathway CO_2 emissions by region

Units: $GtCO_2$/yr



AFOLU: Agriculture, Forestry, and Other Land Use

High-income regions

North America, Europe, OECD Pacific

High-income regions typically have well-developed energy infrastructure, much of which is approaching its end of life and can be phased out. Alternatively, some infrastructure can be repurposed for renewable energy. With extensive fossil-fuelled energy systems, high-income regions typically have highly educated and skilled workforces which can be transitioned into green industries.

High-income regions have the means to, and are expected to, act more quickly to reach net zero. However, these regions will face political challenges arising from the required pace of change and the disruption of entrenched energy interest. In addition, there may be resistance to sending climate finance to middle- and lower-income regions to support the global transition. The global effort to transition to net zero may also challenge the established hegemony of some high-income countries, leading to political uncertainty and further resistance to change.

Middle-income regions

Greater China, Latin America, Middle East and North Africa, North East Eurasia, South East Asia

Middle-income regions often have newly-developed energy infrastructure, which may be financially challenging to transition or phase out before the infrastructure's planned end of life. These additional costs may disincentivize action and can contribute to a slower transition than that of high-income regions. While some countries with less-developed fossil-fuel infrastructure can leapfrog directly to green technology, several regions' countries have abundant fossil-fuel resources subject to transition risks including a loss of export and fiscal revenues that are seen as key to economic development.

The middle-income regions often face issues with weak or underdeveloped social security systems, social protection, and welfare. Lack of social security indicates that many countries in this group are unprepared to manage social changes due to both the transition itself and related environmental and climate changes. For example, governments may be unable to support their populations as they deal with the loss of livelihoods due to industrial obsolescence, or cope with increased energy and service demands to adapt to extreme weather events, or meet rising health service demands caused by pollution and changing climates.

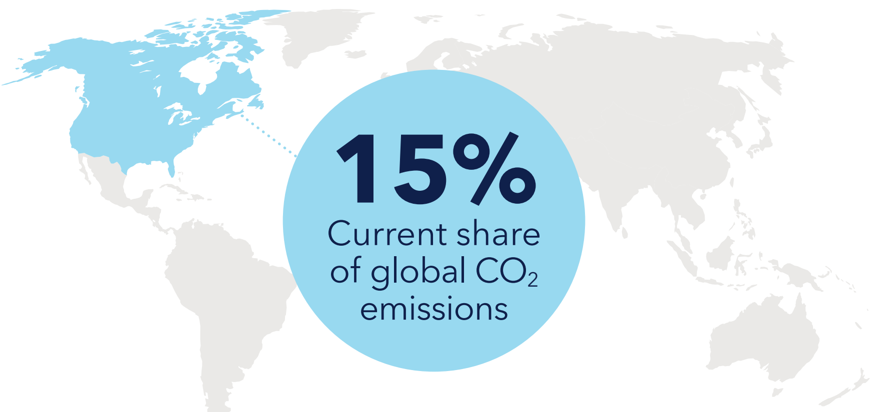
Low-income regions

Indian Subcontinent, Sub-Saharan Africa

Low-income regions, the Indian Subcontinent and Sub-Saharan Africa, face significant energy and development challenges. They are most vulnerable to physical climate change risks but have inadequate fiscal capacity to adapt and bear losses associated with impacts. Their common pathway to net zero is therefore slower as the regions aim to balance poverty alleviation and energy access with emission reductions. Countries in these regions with entrenched social inequalities may struggle to achieve gains in social equity that middle- and high-income regions can through adoption of renewable energy.

On the other hand, a lack of developed energy and transport infrastructure means low-income regions can often leapfrog directly to green technology. Investment and development of a more sustainable pathway can help low-income regions to avoid the carbon lock-in systems that are pervasive in high and some middle-income regions.

5.1 NORTH AMERICA



Net-zero emissions by

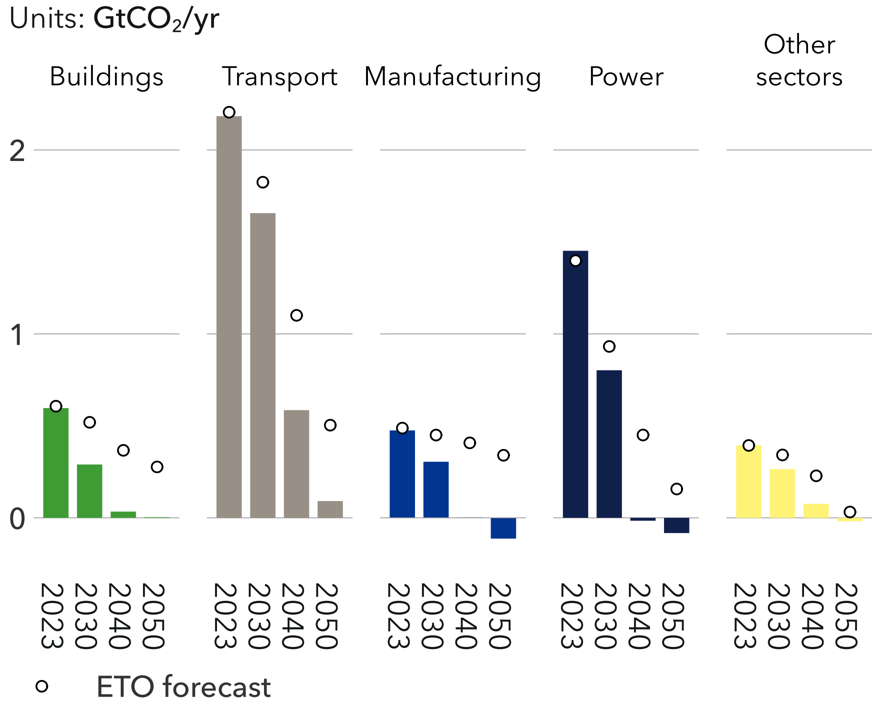
Early/mid 2040s

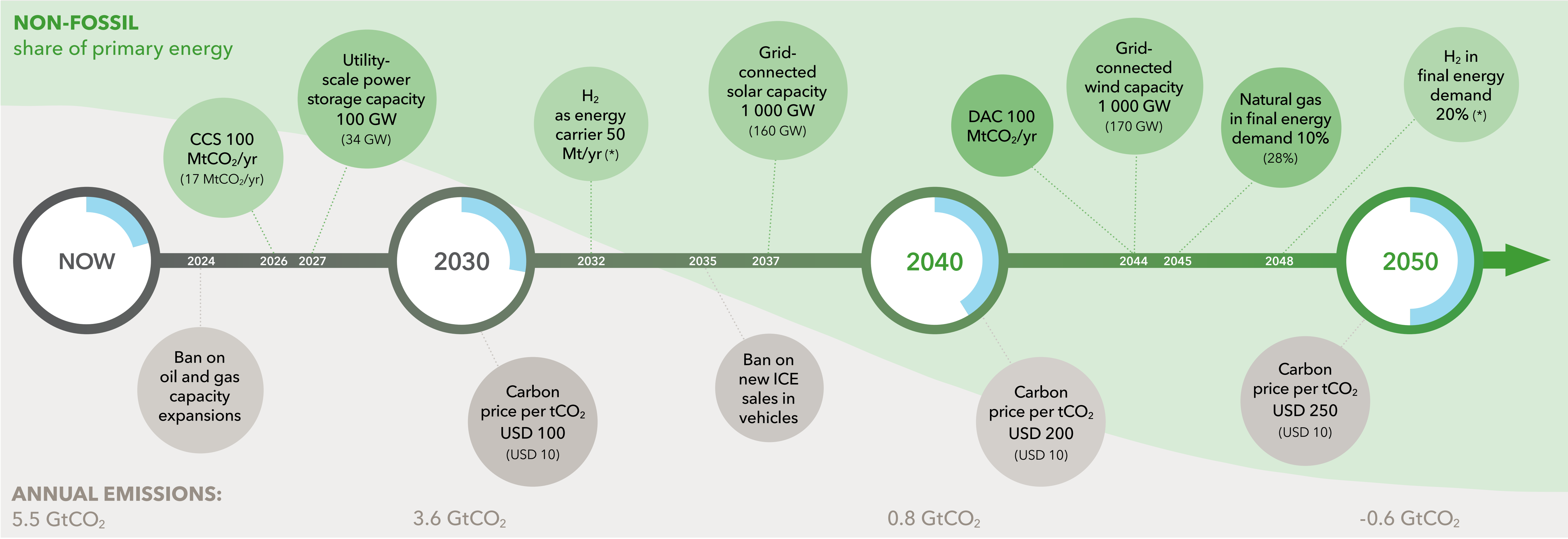
Gap in 2050 with our most-likely ETO forecast

2.0 $GtCO_2$

FIGURE 5.2

North America energy-related CO_2 emissions by sector





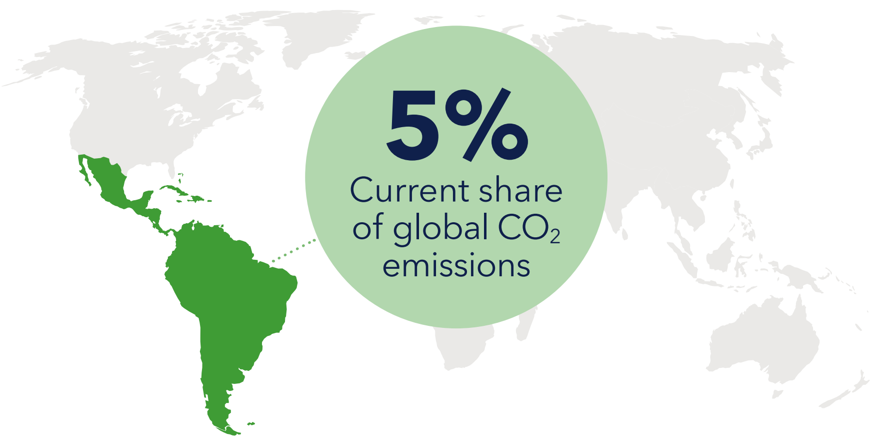
% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

Both the US and Canada have large renewable energy potential and sufficient land area to expand their capacity. Investment in renewable energy can create many green jobs, supported by the countries' strong technology and innovation capacity. An established fossil-fuel industry has a large, trained workforce, with some transferrable skills suitable for green industries. Existing innovation hubs can act as drivers of technological change globally. Equipment and decarbonization solutions manufactured domestically in the US are spurred by the introduction of the *Inflation Reduction Act* (IRA) in 2022.

The region has deeply entrenched fossil fuel interests. The oil and gas industry employs many workers directly and indirectly, and is a big contributor to the economy, making it difficult and politically unpopular to disrupt. Oil and gas consumption is entrenched in society, especially in transport, resulting in widespread resistance to emission-reduction measures like fuel taxes. This is exacerbated by geography and urban planning, where travelling long distances via air or road is normalized and extensive urban sprawl encourages continued car dependency.

Political polarization and resistance to climate policy carry the risk of policy reversal which may hinder implementation of transition strategies. Complexity increases when considering differing regulations between state/province and federal level. Long-term planning and policy implementation require bipartisan support, and collaboration between the various levels of government. Without ongoing support from civil society, implementing climate action and achieving equitable outcomes can be extremely difficult.

5.2 LATIN AMERICA

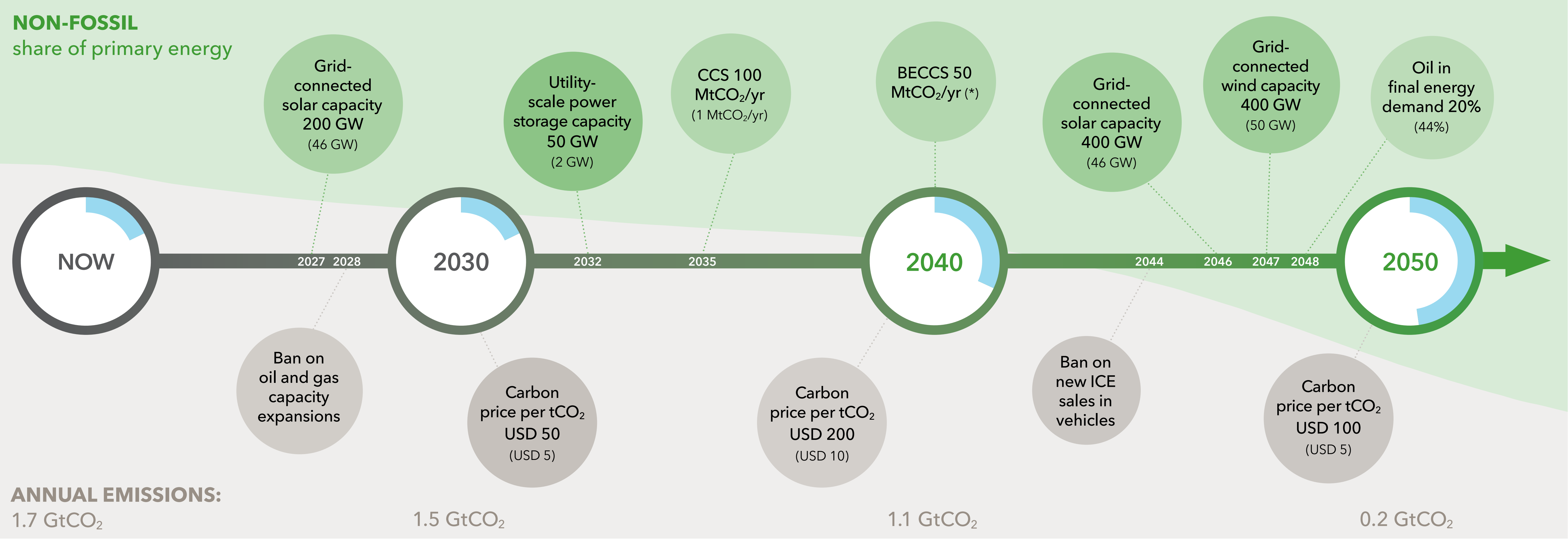


Net-zero emissions by

Early/mid 2050s

Gap in 2050 with our most-likely ETO forecast

1.2 $GtCO_2$

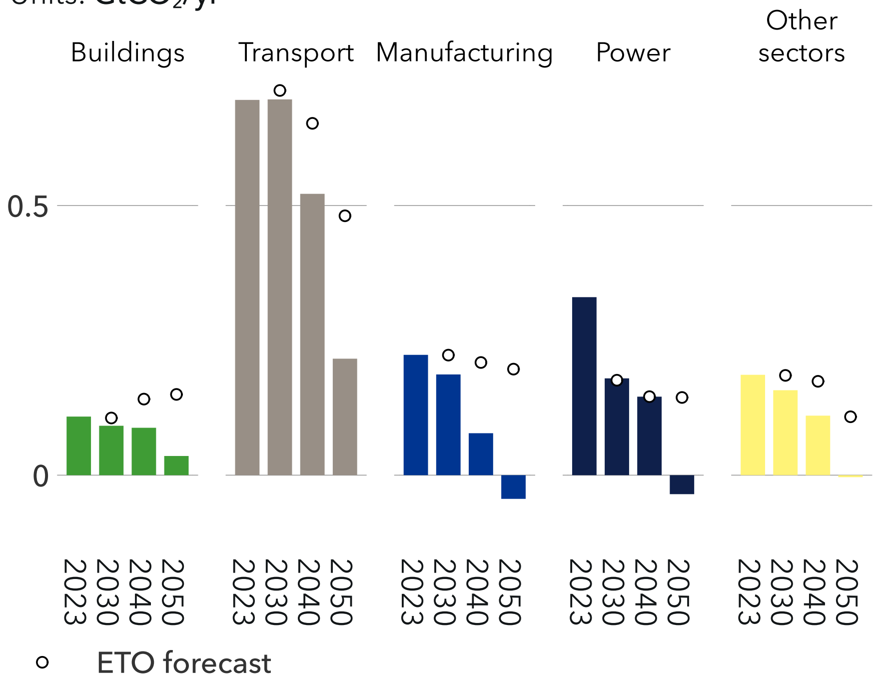


% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

FIGURE 5.3

Latin America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr

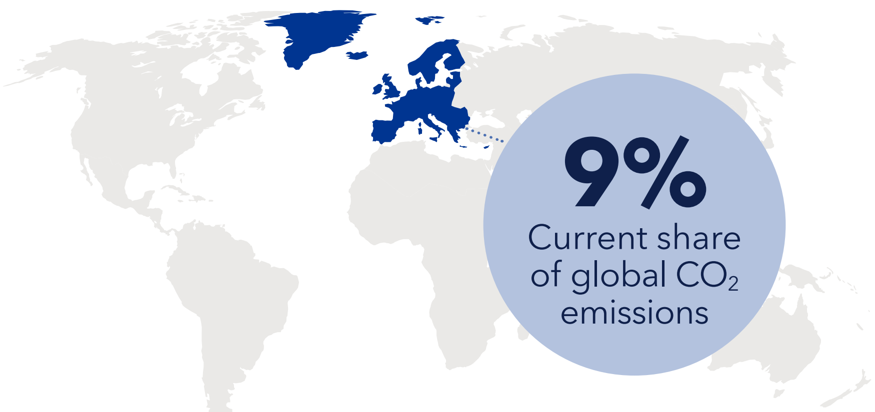


The Latin America region has the opportunity to expand its high levels of existing renewable energy capacity due to favourable geography and rich natural resources. There is great potential for solar, wind, hydropower, biomass, and geothermal energy, and low-carbon fuels, as well as a wealth of minerals necessary for the transition like copper and lithium. With careful stewardship, for example by involving indigenous peoples, large areas of rainforest can act as strong net carbon sinks.

Many economies in this region are dependent on agriculture and natural resources, both of which are particularly vulnerable to production challenges as climate change-related disasters increase in frequency and intensity. Declines in these industries may lead to significant changes to the employment mix, resistance to change, and increased insecurity for workers. Climate damage will exacerbate the large social and economic inequalities which exist in the region. Adapting to and mitigating these environmental changes will take substantial investment and time.

A major challenge facing countries in Latin America is the history of corruption and environmental crime. Corruption can facilitate environmental crime such as illegal mining, logging, and dumping of waste and pollutants. Subsidies and grants intended for renewable energy projects have been targets for fraud and vested interests. Corruption affects the planning and implementation of long-term environmental and climate policy, as well as the enforcement of existing regulations. Transparency and accountability in governance and policy implementation is a crucial part of the transition.

5.3 EUROPE



Net-zero emissions by

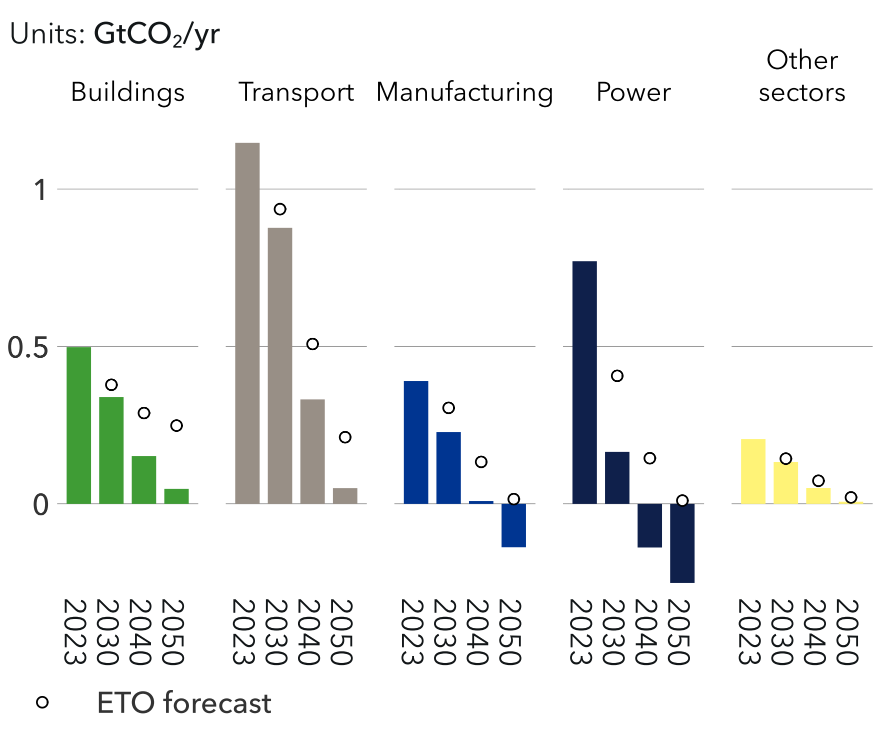
Early 2040s

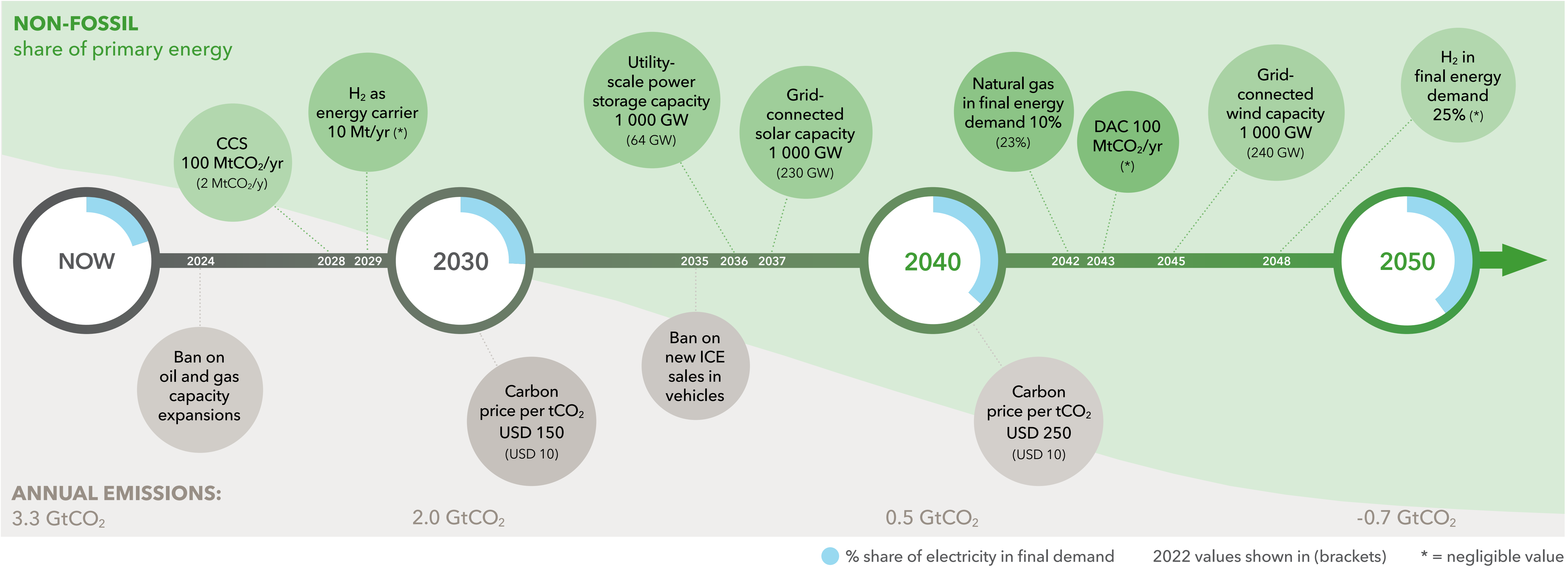
Gap in 2050 with our most-likely ETO forecast

1.1 $GtCO_2$

FIGURE 5.4

Europe energy-related CO_2 emissions by sector



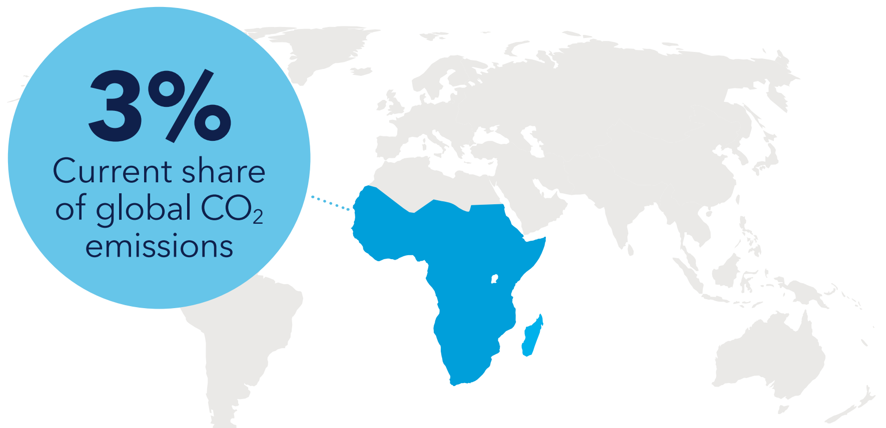


Europe has a strong advantage in its high levels of regional collaboration, exemplified by the EU's strong political will to pursue net zero. The EU has ambitious goals to transition away from fossil fuels to renewable energy faster than any other region and has robust implementation capacity to do so. Due to these centrally guided goals, countries in the region often embed climate policy into their decisions. However, because there are many member states that must agree, EU policymaking takes time and stringent policies can become diluted.

A challenge facing Europe is its dependence on energy imports and related energy security concerns. Although there is growing renewable energy production, oil and gas imports remain high. Russia was the largest oil and gas exporter to Europe, but this has come to a hard stop since the war in Ukraine. The war made near-term energy security an even higher priority, triggering measures to further increase shares of renewables and nuclear in the energy mix. Europe is also dependent on international supply chains for other commodities like primary and rare earth metals which are necessary for the transition.

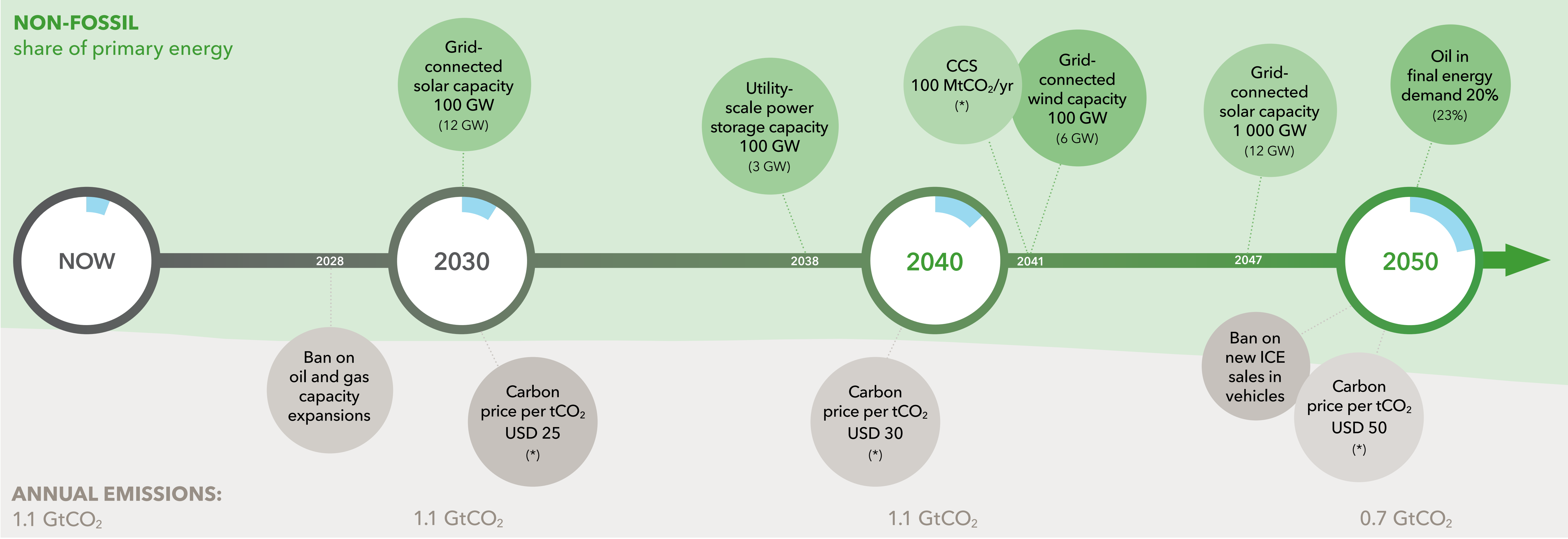
Political shifts in Europe due to factors like the cost-of-living crisis may lead to increased resistance to climate policy and finance. Closer scrutiny of economic policy may lead to reduced support for climate finance and development assistance for low-income regions, where the EU is the largest global contributor. As decarbonization deepens, emissions cuts become more tangible, potentially triggering resistance to specific laws like emissions limits for cars, pollution limits for agriculture, and nature conservation measures.

5.4 SUB-SAHARAN AFRICA



Net-zero emissions by
2060

Gap in 2050 with our most-likely ETO forecast
0.8 $GtCO_2$

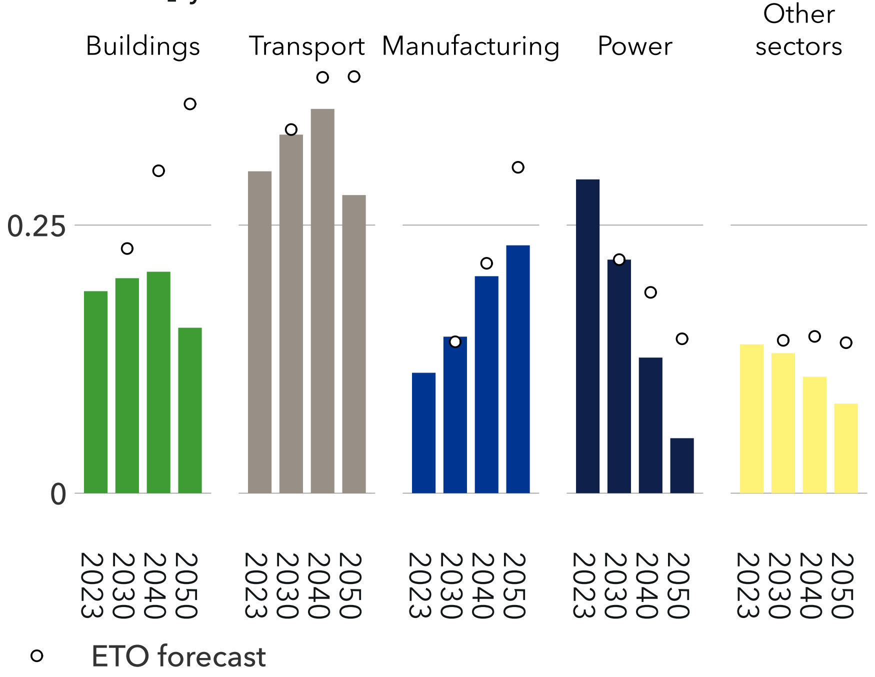


% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

FIGURE 5.5

Sub-Saharan Africa energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr

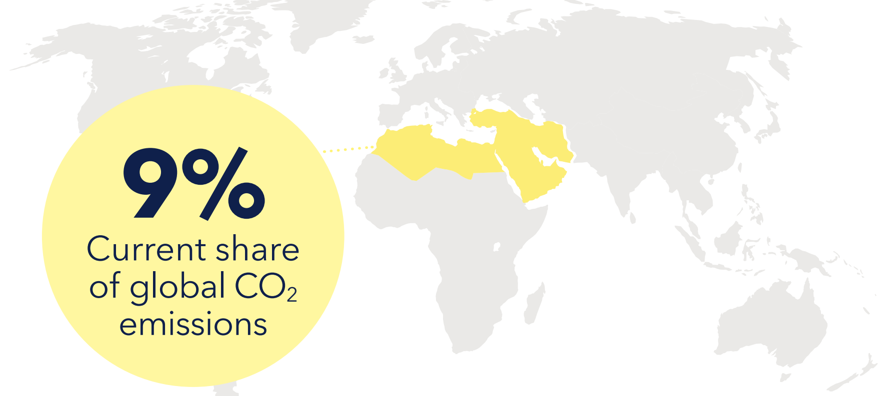


Sub-Saharan Africa is the region with the lowest access to electricity and clean energy. This has implications for health, poverty alleviation, education, and social and economic development. For example, lack of access to clean cooking fuels causes well above one million deaths per year. Household pollution disproportionately affects women and girls, who spend more time engaged in household labour, and impedes their access to social, health, and education services. Energy poverty is compounded by food security and water scarcity issues experienced in the region.

An underdeveloped fossil-fuel infrastructure contrasts with abundant resources, particularly solar and minerals necessary for the transition, which provides a big opportunity to leapfrog to green technology and energy production. The region's demographic skews young, meaning there is ample affordable labour to drive the transition given sufficient training. The region is also likely to receive financial support and investment from high-income countries, which is necessary to achieve energy access and implement renewable energy technology.

Corruption is 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 failed spectacularly across the subcontinent. 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).

5.5 MIDDLE EAST AND NORTH AFRICA

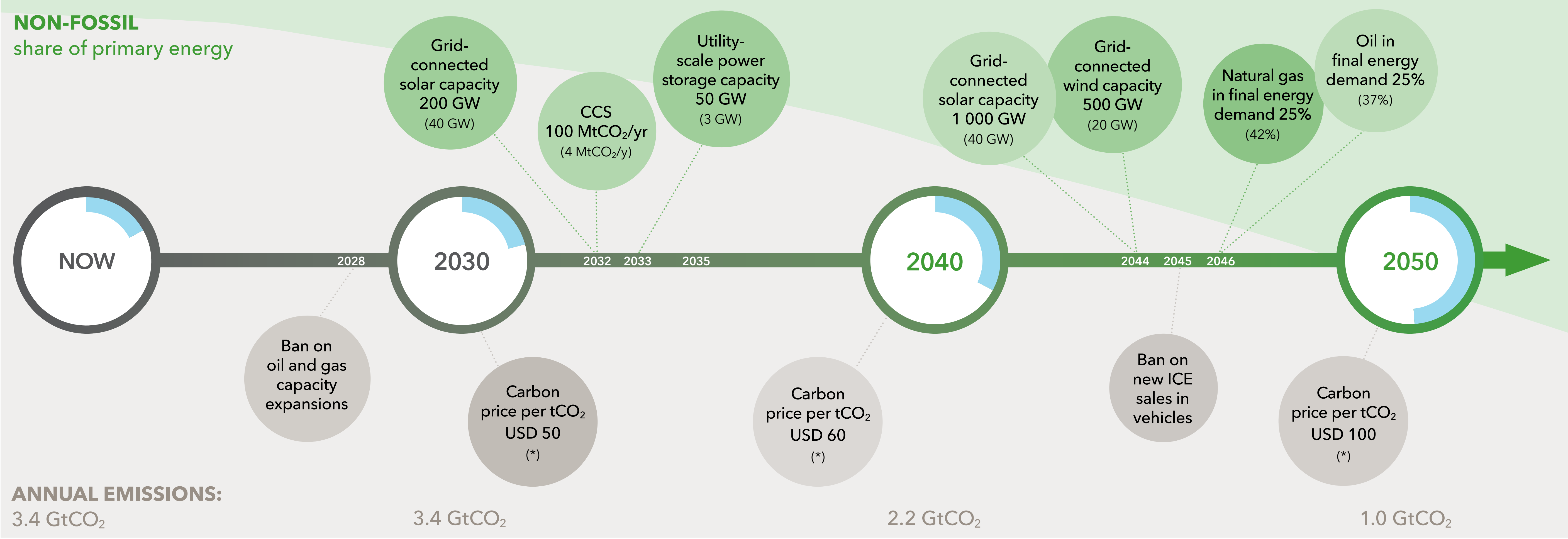


Net-zero emissions by

2060

Gap in 2050 with our most-likely ETO forecast

2.1 $GtCO_2$

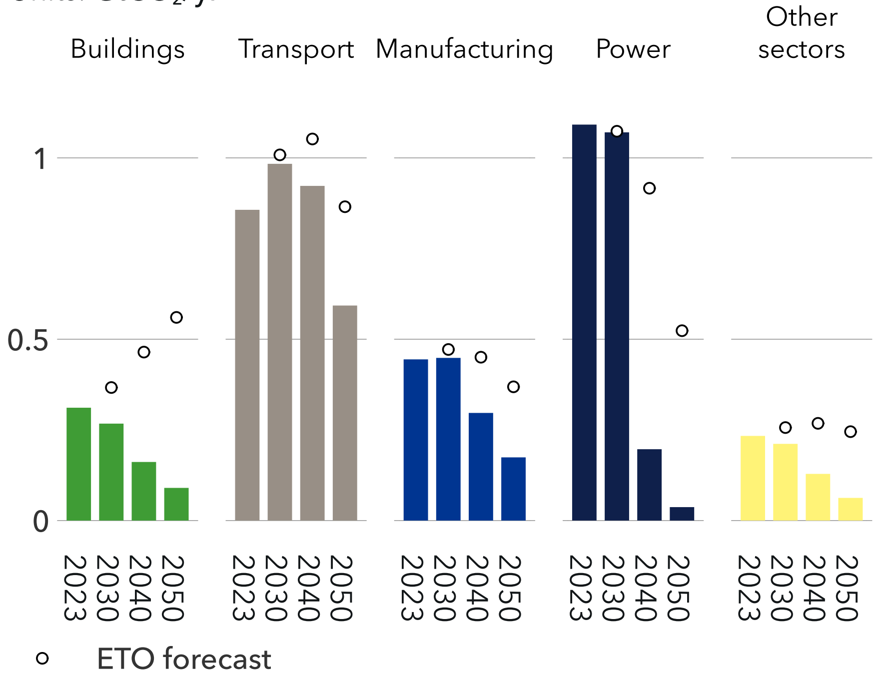


% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

FIGURE 5.6

Middle East and North Africa energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr

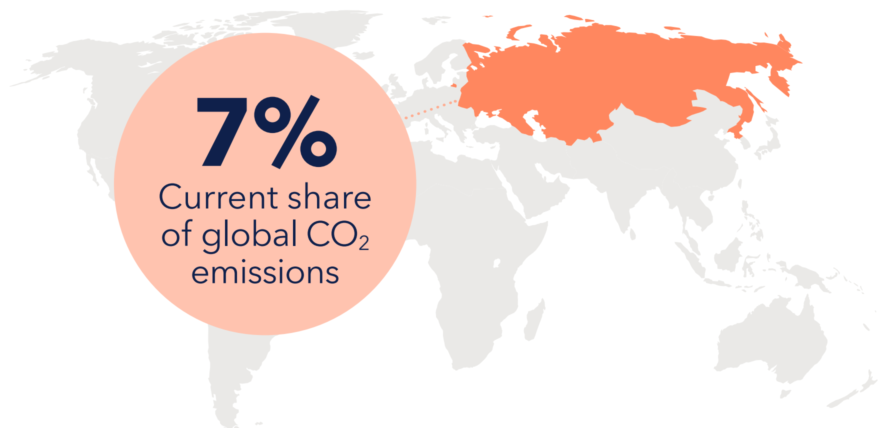


Widespread political unrest and conflict hinder the implementation of long-term climate and development plans, especially when resources are diverted from decarbonization or environmental protection to more immediate security concerns. Instability also disrupts economic activity and displaces populations. Consequently, resources are strained, especially among energy importers, and governments are unable to provide their populations with reliable clean energy, stable and green jobs, and access to social services.

The region's economy is heavily dependent on fossil fuels, with the region accounting for about a third of global production of oil and gas. Widespread fossil-fuel and energy subsidies can be shifted to accessible and affordable clean energy to leverage the region's vast renewable potential, especially in solar. Hydrocarbon producers can draw on existing fossil-fuel infrastructure and knowledge to expand the capacity to produce and export low-carbon hydrogen, particularly blue hydrogen with CCS.

The region does not currently have sufficient carbon pricing to incentivize economy-wide decarbonization. Stimulating investment in CCS may create jobs which existing skilled workers in oil and gas could transition into. Producers who reduce emissions may be able to continue export of oil and gas in the short term to regions like Europe. However, reliance on CCS as an emissions reduction measure may prolong dependence on oil and gas production in the region, ultimately increasing emissions and slowing the transition to net zero.

5.6 NORTH EAST EURASIA



Net-zero emissions by

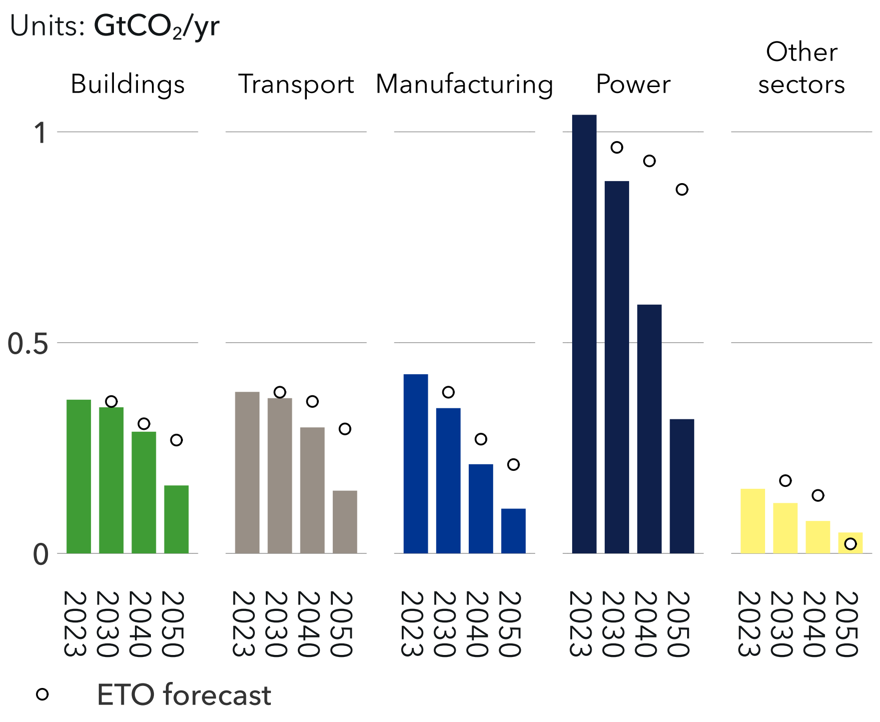
2060

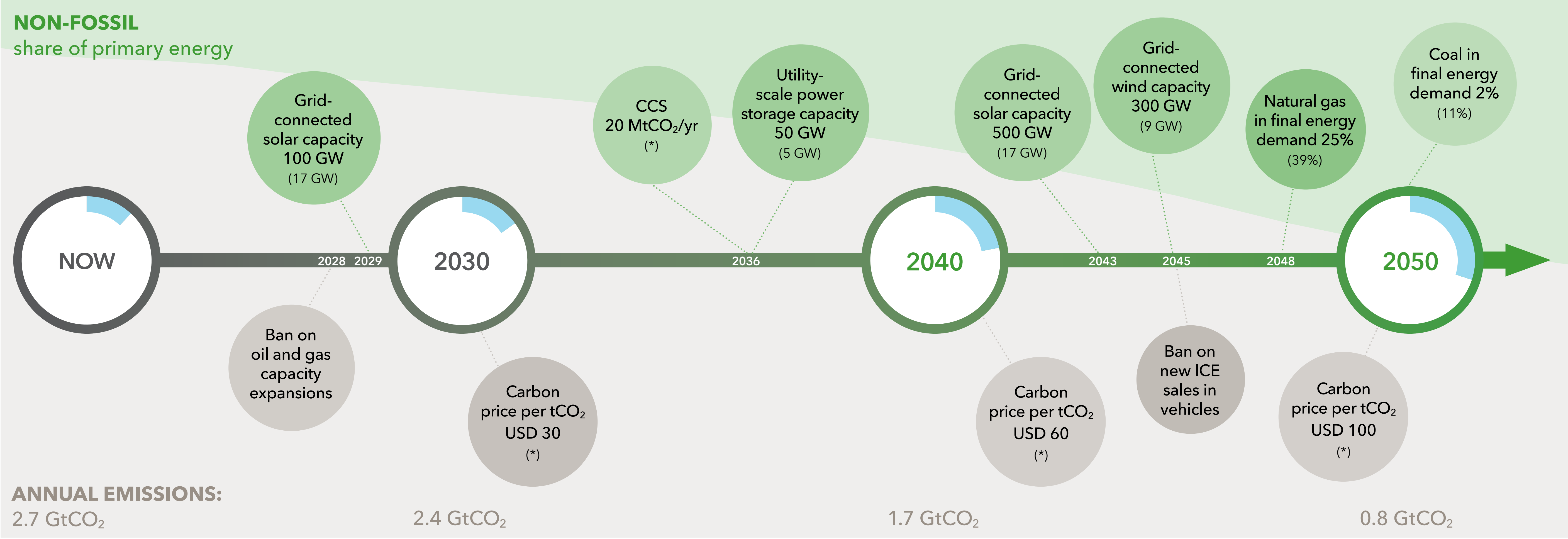
Gap in 2050 with our most-likely ETO forecast

1.0 $GtCO_2$

FIGURE 5.7

North East Eurasia energy-related CO_2 emissions by sector





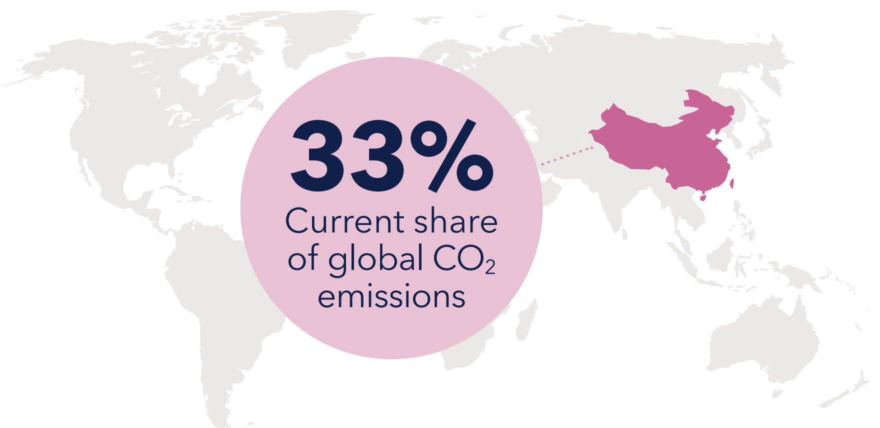
% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

Russia's invasion of Ukraine has complicated the region's geopolitical position. The conflict has led to sanctions on Russia and strong incentives to reduce reliance on Russian oil and gas, especially within Europe. Political uncertainty makes long-term planning and implementation of climate and environmental policy difficult in a region which is already lagging on transition issues. Access to technologies may be more difficult, although relations with China remain good.

The region is heavily dependent on oil and gas and is a top global producer with extensive infrastructure and widespread subsidies applied to fossil fuels. Production is primarily concentrated in Russia, the dominant economy in the region, and Kazakhstan. The reliance on fossil fuels is both a cause and consequence of the region's lacklustre transition pace. Transitioning away from fossil fuels will have a huge effect on the region's economies, employment mix, infrastructure, and energy security.

The region is rich in mineral resources, many of which are necessary for the production of battery and other renewable technologies. With global demand for these minerals increasing, the region has a significant opportunity to use its existing mining infrastructure to meet this demand and generate export income. Furthermore, the region is home to large areas of boreal forests, which provide huge potential as a carbon sequestration measure.

5.7 GREATER CHINA

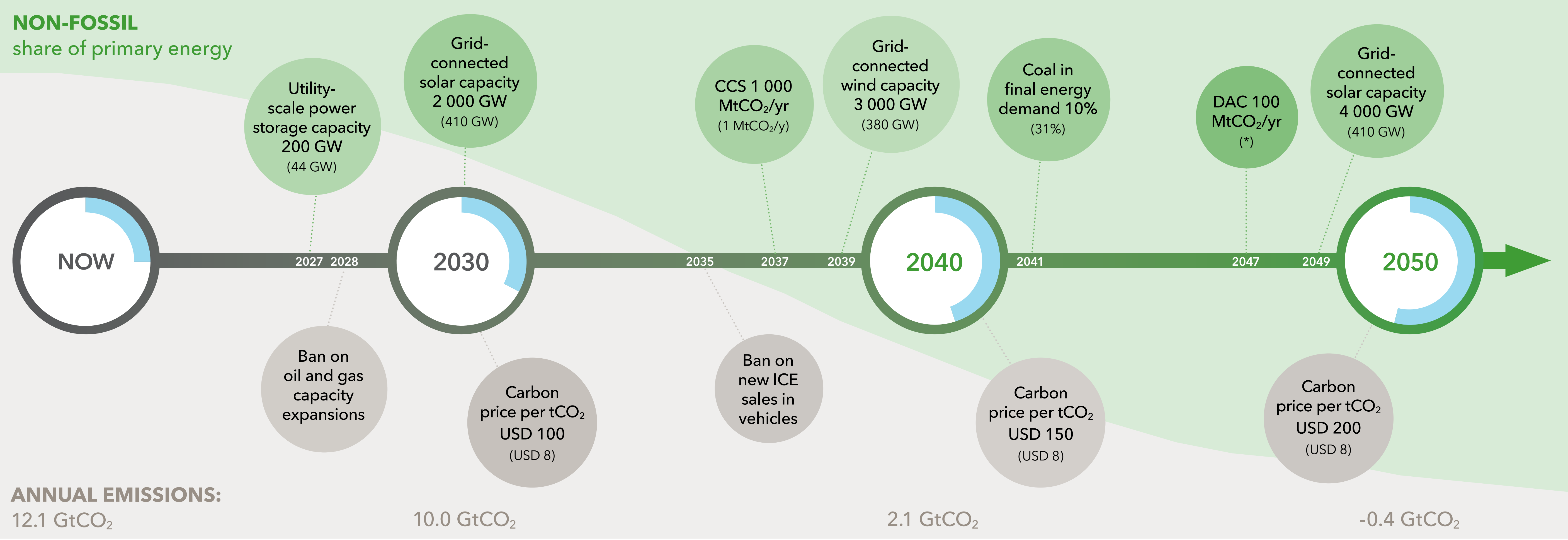


Net-zero emissions by

Late 2040s

Gap in 2050 with our most-likely ETO forecast

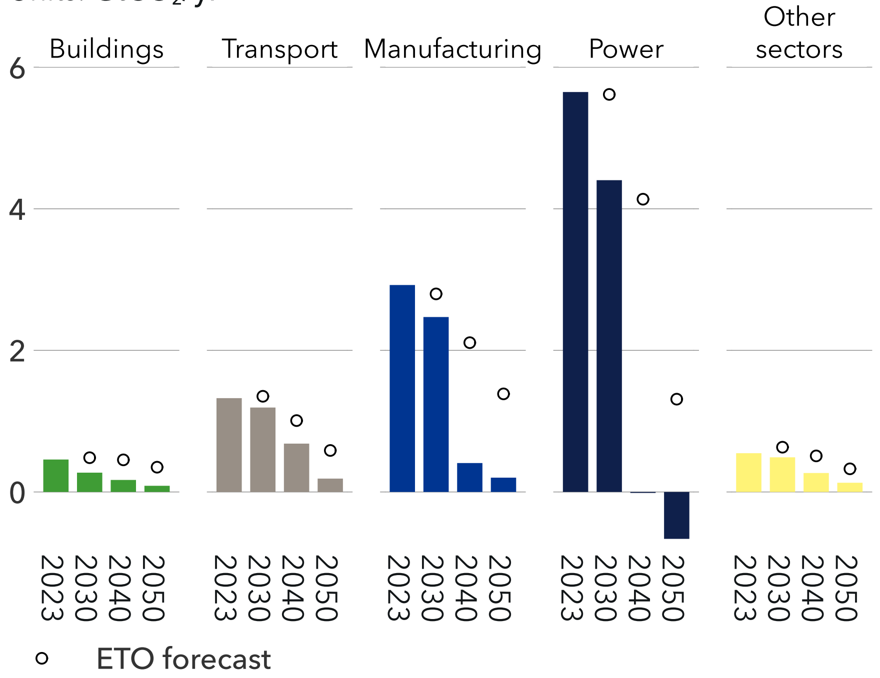
5.3 $GtCO_2$



% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

FIGURE 5.8

Greater China energy-related CO_2 emissions by sector

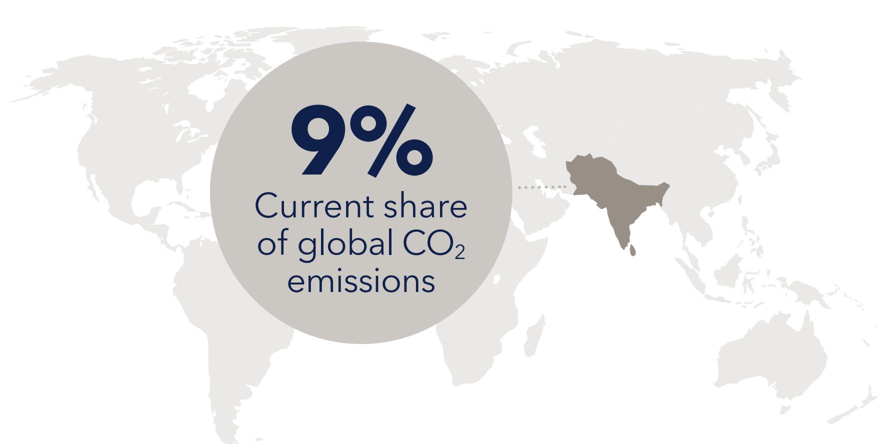


The political stability provided by the central government lends itself well to long-term planning and implementation capacity of energy, climate, and environmental policies, which may be more challenging in countries with frequent leadership changes. On the other hand, central planning places pressure on the government to get things right in the first place. Regionalization and rising protectionism are challenging global cooperation and the present almost unlimited market access is under threat.

China is the largest investor in renewable energy globally, and its transition capacity is large. It has developed very high skills and capabilities in renewables, has advanced manufacturing capacity, and has a strong knowledge base on infrastructure, including battery storage and interconnectors. Consequently, China is an important link in the global supply chain for renewable energy technology and has the opportunity to support the continued uptake of renewables. This stimulates continued economic growth in China when use of renewables increases globally.

The region is highly dependent on coal, and currently uses more than half of the world's supply. Coal is vital for the region's energy production and energy security, making it difficult to divest from. However, given the region's expertise in renewables, there is a big opportunity to decarbonize and reduce coal dependency. The region also has a rapidly growing hydrogen industry, which is emerging as a strong opportunity for China to decarbonize some sectors and provide more green jobs. Emissions from hydrogen production itself can be reduced by leveraging existing renewable energy capabilities.

5.8 INDIAN SUBCONTINENT

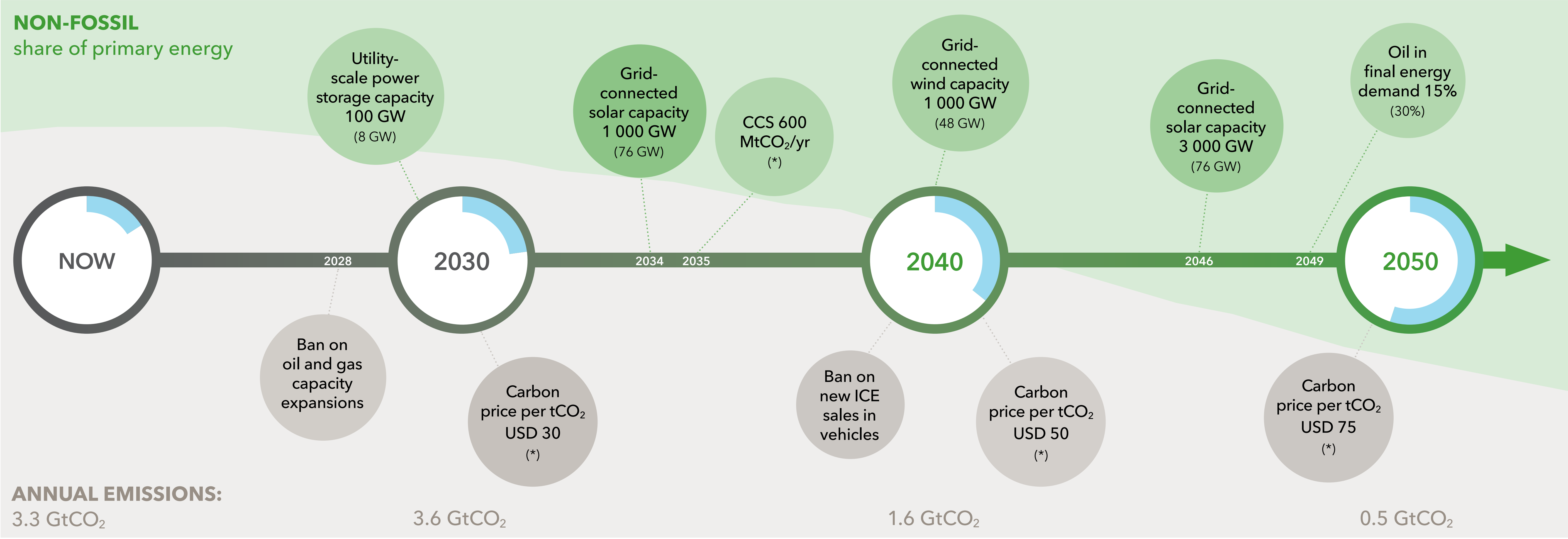


Net-zero emissions by

Mid 2050s

Gap in 2050 with our most-likely ETO forecast

3.9 $GtCO_2$

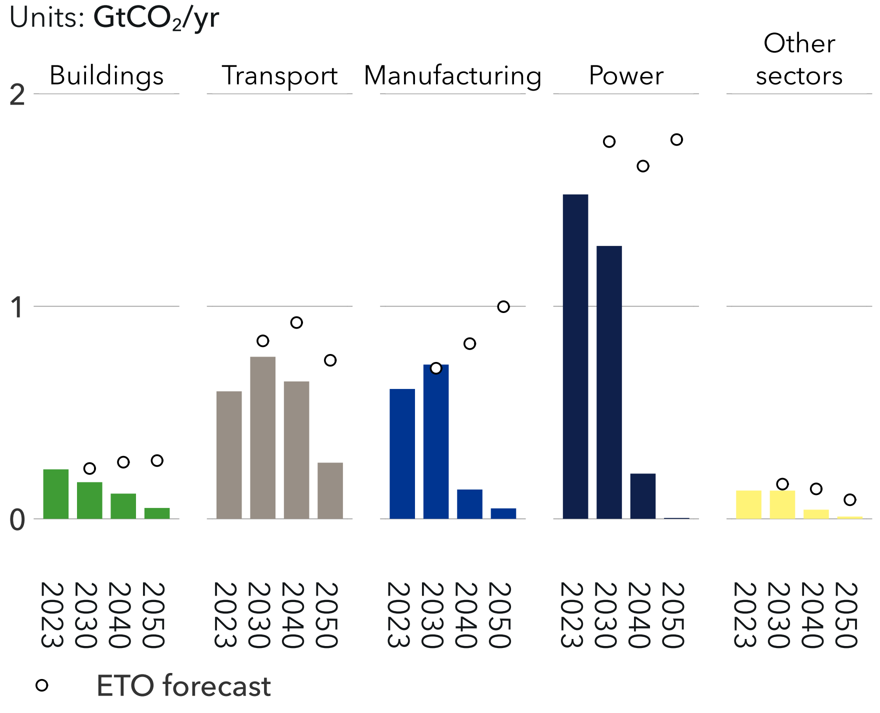


% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

FIGURE 5.9

Indian Subcontinent energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr

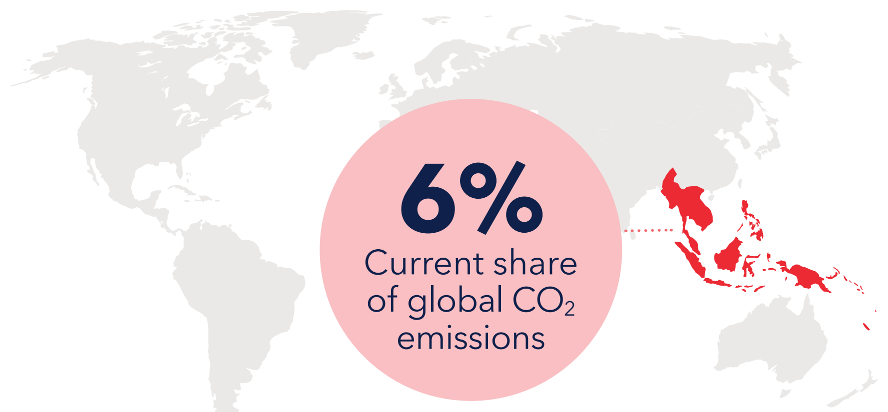


Rapid economic growth across the Indian Subcontinent is widening the gap between rich and poor, although it is also lifting many millions out of dire poverty. However, these advances could be reversed by climate change effects, not least extreme heat events and flooding, which disproportionately affect the poor. There is rising pressure for the subcontinent to deliver a transition that both addresses inequalities and widens access to clean and reliable energy as well as opportunities for stable jobs. A vital part of the transition is that no-one is left behind.

Growing population density and rapid urbanization is placing a strain on access to energy and other services like health and transport. However, this provides opportunities for efficient energy use in buildings, and especially in the transport sector. Growing demand for transport and increased access to vehicles provides a huge opportunity to avoid increased use of ICEs in favour of electric two- and three-wheeler vehicles to reduce emissions and urban air pollution. Dense urban regions mean that implementation of low emission public transport is a possibility for meeting rising urban transport demands.

The Indian Subcontinent is currently dependent on fossil fuels, and projected growing emissions may result in increased carbon lock-in if investment in fossil fuel infrastructure continues. Given that industrialization in India lags China's industrial advance by at least two decades, many more opportunities for non-fossil energy exist, and these come at a much lower cost. The potential is there for a modern, renewable-dominated energy system which will also reduce emissions, pollution, and pollution-related health issues. However, projects are capital-intensive and meeting investment needs require foreign investment support or derisking.

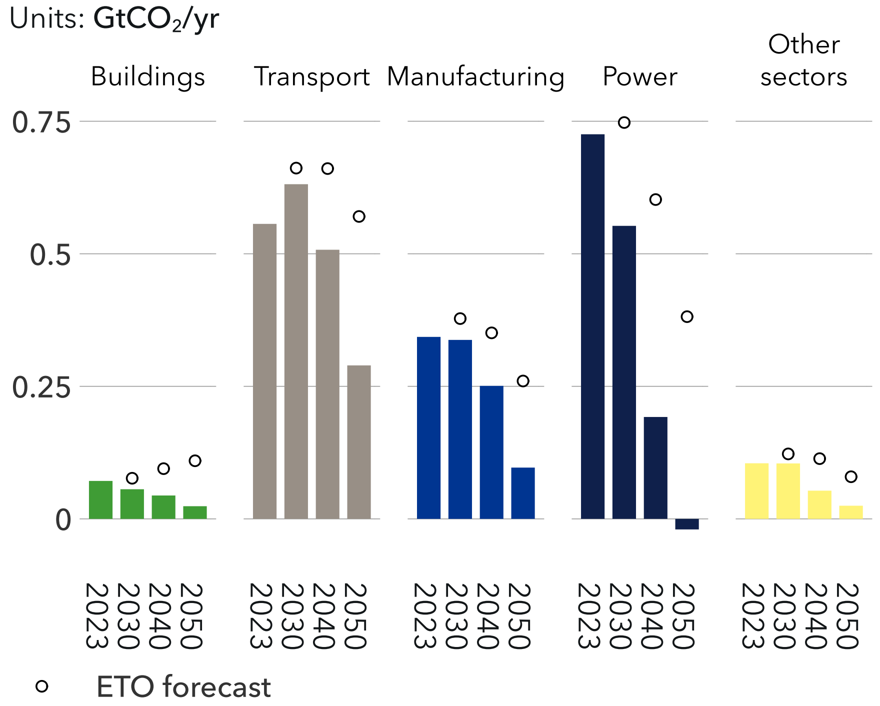
5.9 SOUTH EAST ASIA

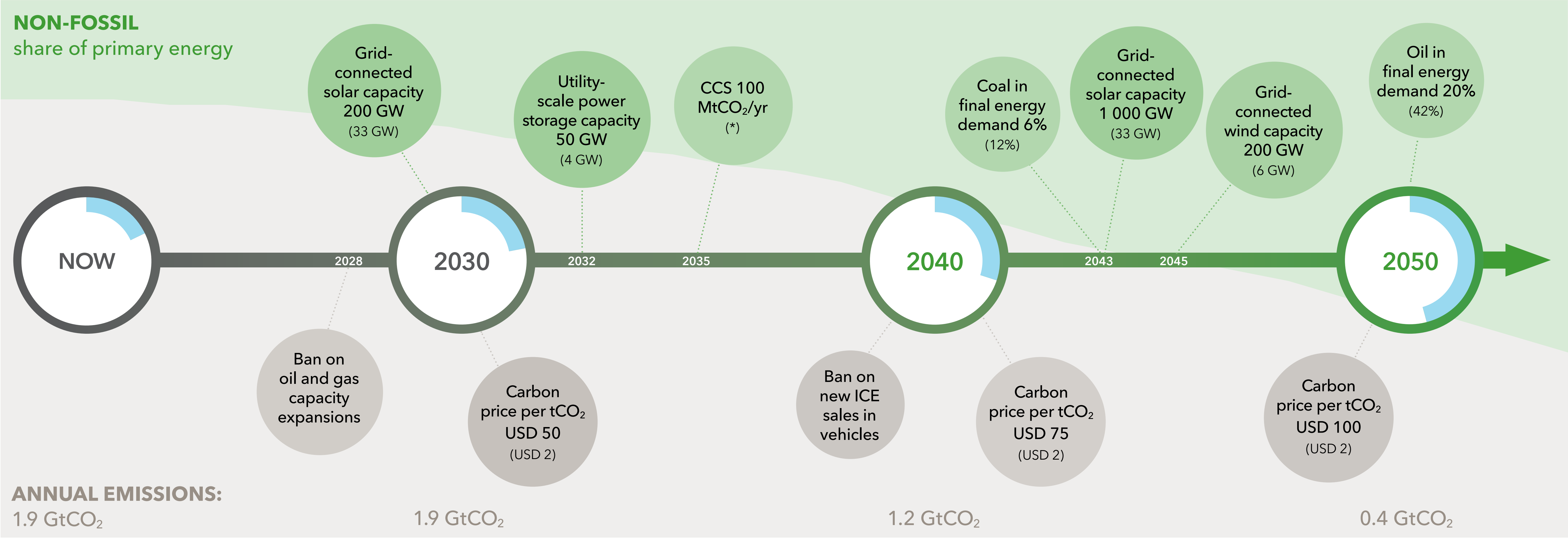


Net-zero emissions by
Mid 2050s

Gap in 2050 with our most-likely ETO forecast
1.2 $GtCO_2$

FIGURE 5.10
South East Asia energy-related CO_2 emissions by sector





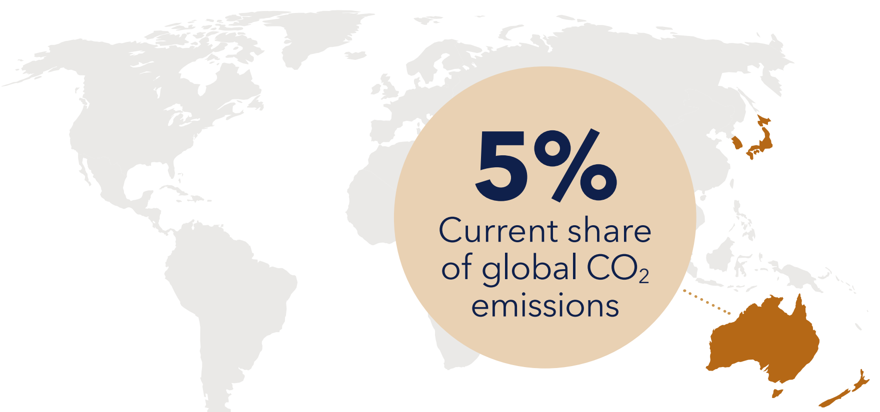
% share of electricity in final demand 2022 values shown in (brackets) * = negligible value

South East Asia is a highly diverse region with a range of income levels varying from high in Singapore to lower-middle in Myanmar, Cambodia, and Lao PDR. Social and economic inequality is an issue between and within countries, as rapid economic growth has intensified existing social disparities. Countries in the region must collaborate to plan and implement climate and environmental policy that spreads both the benefits and burdens of the transition in a fair way. One such benefit is the opportunity to diversify industry to become an alternative to China as an affordable production hub.

Economic growth has seen a rapid increase in access to quality education in South East Asia, despite variation within the countries. Relative to other middle-income regions, the region has comparatively high levels of education access and gender parity from primary to tertiary education. This places the region in a strong position to meet the growing skilled labour demands of the transition. However, this advantage is countered by above average rates of 'brain drain', with educated and skilled workers emigrating to high-income regions.

Phasing out coal will have a big impact on economies and jobs in the region. Indonesia is the world's leading thermal coal exporter and Vietnam is an important coal producer. Coal mines tend to be concentrated in specific areas in these countries, leading to an unequal distribution of impacts to livelihoods and communities. For importers who rely on coal for energy generation like the Philippines and Malaysia, phasing out coal may lead to displacement of jobs, and poorer countries may struggle to afford the higher upfront investments of alternative supply sources.

5.10 OECD PACIFIC



Net-zero emissions by

Early/mid 2040s

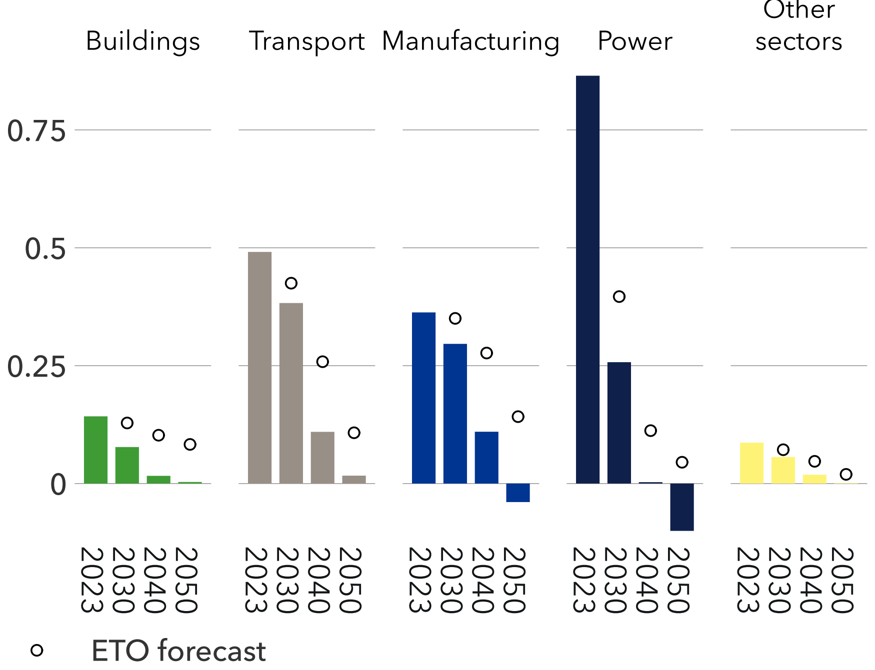
Gap in 2050 with our most-likely ETO forecast

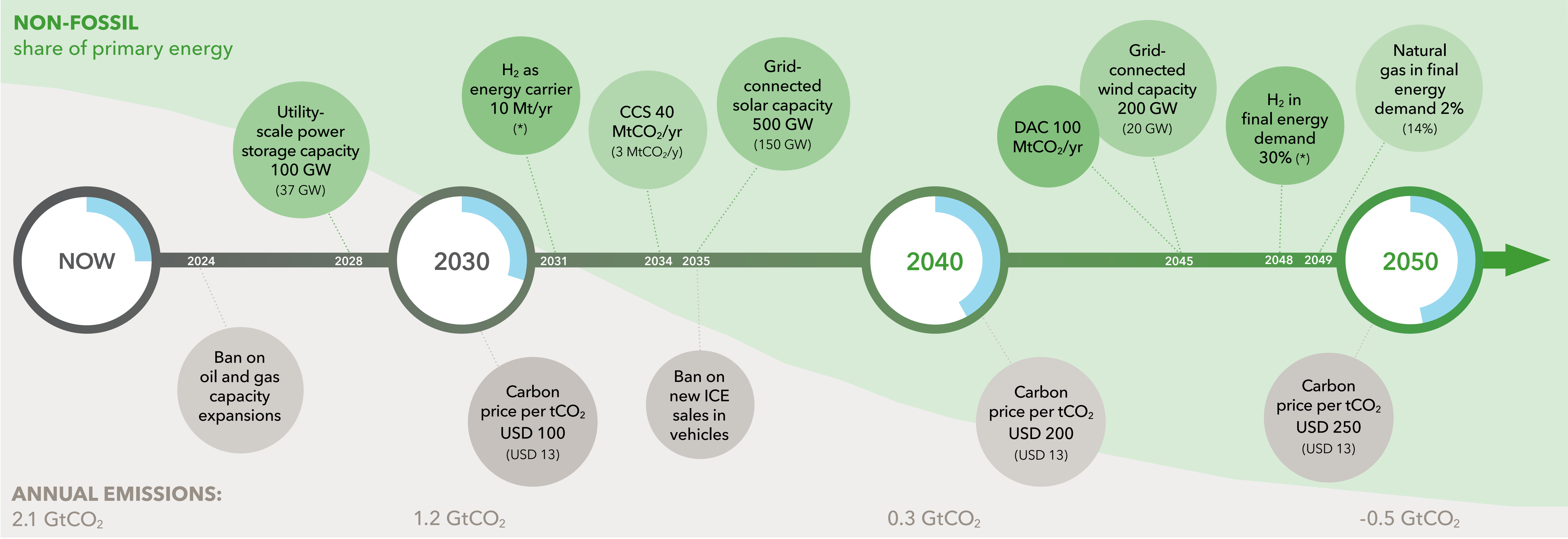
1.0 $GtCO_2$

FIGURE 5.11

OECD Pacific energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr





% share of electricity in final demand   2022 values shown in (brackets)   * = negligible value

The economies in OECD Pacific have historically been heavily reliant on fossil fuels and thus face a major challenge in reducing fossil fuel dependency and diversifying their economies. This challenge affects importers and exporters: Australia's economy is highly dependent on export of coal and LNG; New Zealand, Japan, and South Korea's energy mix is dominated by imported coal, oil, and LNG. Moving away from fossil fuels will have an adverse impact on workers and communities across these countries and should be mitigated as part of the transition.

Countries in this region have high renewable energy potential, with access to abundant wind resources onshore, and plenty of coastline to capitalize on the growing offshore wind market. Australia has very high solar irradiation levels, and rooftop solar is already installed at almost one in three homes. Additionally, there are burgeoning hydrogen industries in Australia, New Zealand, and South Korea. Growth of renewable energy industries will create stable and green jobs, and many workers already have the skills and training necessary to work in green industries.

Place-based policies are used to enhance the economic, social, and environmental performance of a specifical area. This could be a useful mechanism for countries in the region to achieve more equitable distribution of benefits and burdens across people and places. All four countries have stable governance, increasing the capacity to implement policy. For example, place-based policy could target coal mining regions in Australia to ensure that communities and workers there do not get left behind, and foster growth of new industries in specific regions like hydrogen production in South Korea.

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Historical data

This work is partly based on the World Energy Balances database developed by the International Energy Agency© OECD/IEA 2023, but the resulting work has been prepared by DNV and does not necessarily reflect the views of the International Energy Agency. For energy-related charts, historical (up to and including 2022) numerical data is mainly based on IEA data from World Energy Balances© OECD/IEA 2023, www.iea.org/statistics, License: www.iea.org/t&c; as modified by DNV.

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, based in Oslo, Norway. In addition, we have been assisted by internal and external energy transition experts, with the core names listed below:

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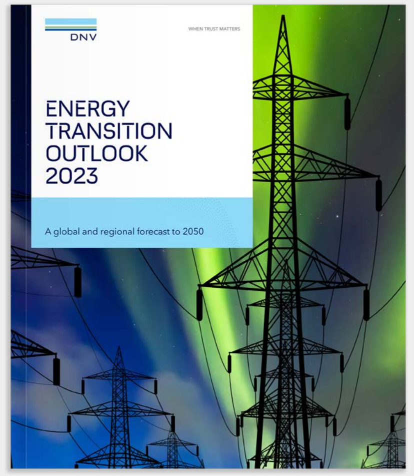

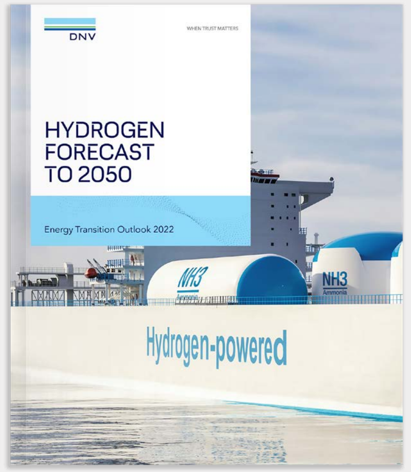

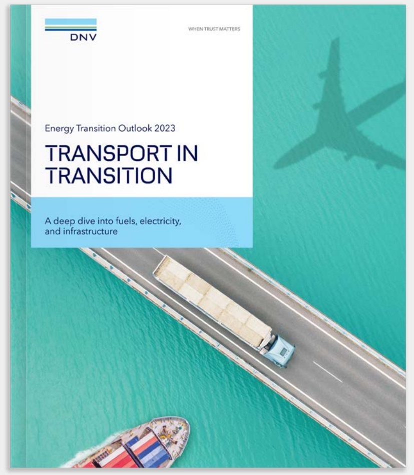

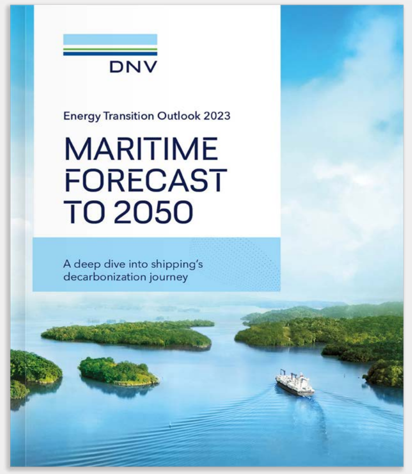

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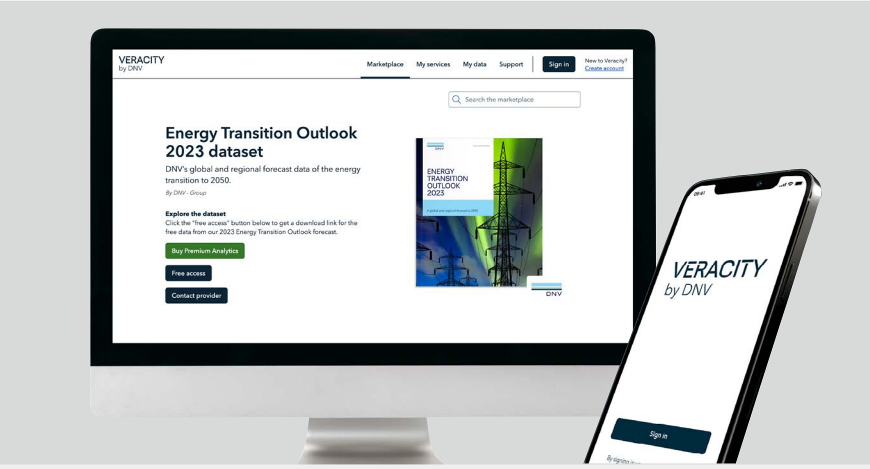

All the forecast data in DNV's suite of Energy Transition Outlook reports, and further detail from our model, is accessible on Veracity – DNV's secure industry data platform.

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