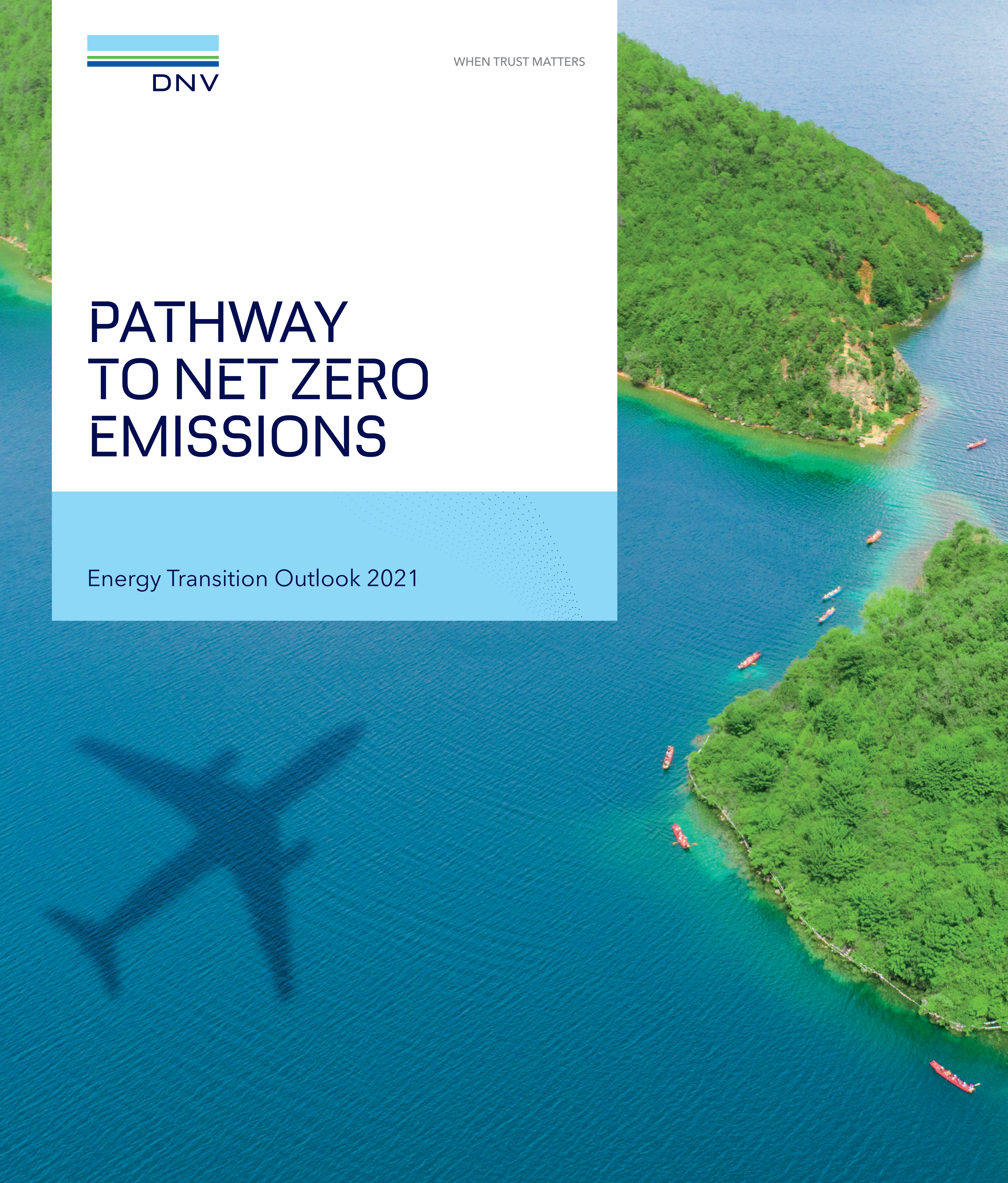
WHEN TRUST MATTERS

PATHWAY TO NET ZERO EMISSIONS

Energy Transition Outlook 2021



FOREWORD

Zero is not enough. That is because, try as they might, many developing nations and hard-to-abate sectors will not be able to achieve zero emissions by 2050 – the critical threshold for the world to stay within 1.5°C of warming.

Developed nations, leading companies and easy-to-electrify sectors are therefore going to have to go *below* zero *before* 2050. That is a key finding of our analysis of what it will take to achieve the ambitions of the Paris Agreement.

I want to stress that our *Pathway to Net Zero Emissions* is not the most likely pathway, but a plausible pathway. Elsewhere, in our *Energy Transition Outlook* (ETO), we set out our forecast which we see as the 'most likely' pathway for the world's energy future, through to 2050. We have issued our ETO annually for the last five years and have repeatedly warned that the energy transition we see – and which some commentators have labelled 'unrealistically fast' – leads to a global warming of 2.3°C by the end of this century. In other words, a dangerous outcome for humanity.

In this publication, which is a first from DNV, we draw on our ETO model to answer the question: "How can the world achieve 1.5°C within the bounds of techno-economic and political feasibility?"

The short answer is that the world has sufficient technological capability and economic capacity to reach the 1.5°C target. Electricity, powered by wind and solar, will be the dominant technology. Economically, the world will have to spend an additional amount close to 1% of GDP on energy infrastructure. That is significant, but not a roadblock. In the short term, there will be relatively high costs due to incentives and taxes needed to put immature technologies in motion, like we saw for solar PV and wind 25 years ago. The critical constraints – what the world lacks – are time and tough policy. Time-wise, we have to act <u>now</u>, at the beginning of the "decade of action", and at speed and scale to avoid the mounting costs of inaction. Policy-wise, tough mandates and bans lie ahead, as well as creative regulations that nudge desired behavioural changes like flying less, using more electricity for road transport, and actively practicing circularity.

Readers may be surprised to find in our Pathway a 2050 energy mix that includes 21% of fossil fuel in the system. Therefore, you will find that some 20% of emissions cuts will have to be in the form of carbon capture and carbon removal. That is because, in our view, it is infeasible to transition to a completely fossil-free energy system by 2050.

I am well aware of the great challenge that going below zero poses. For DNV, and many of our customers, it means reducing our own emissions to zero and going well beyond that before 2050. For some nations, like the US, it means that the announced ambitions to decarbonize the power system by 2035 and the economy by 2050 are not enough. But if those who can don't go below zero, and in doing so lower the cost and raise the performance of critical technology, we will never limit global warming to well below 2°C. For example, for Sub-Saharan Africa to stretch to a 23% decarbonized energy system by 2050 it will require both extraordinary commitment from the region itself, and reliance on funding and technology learning and transfer from faster-transitioning regions.

1.5°C is within our grasp only if everybody lifts what they can.

Remi Eriksen

Remi Eriksen

Group president and CEO

DNV

CONTENT

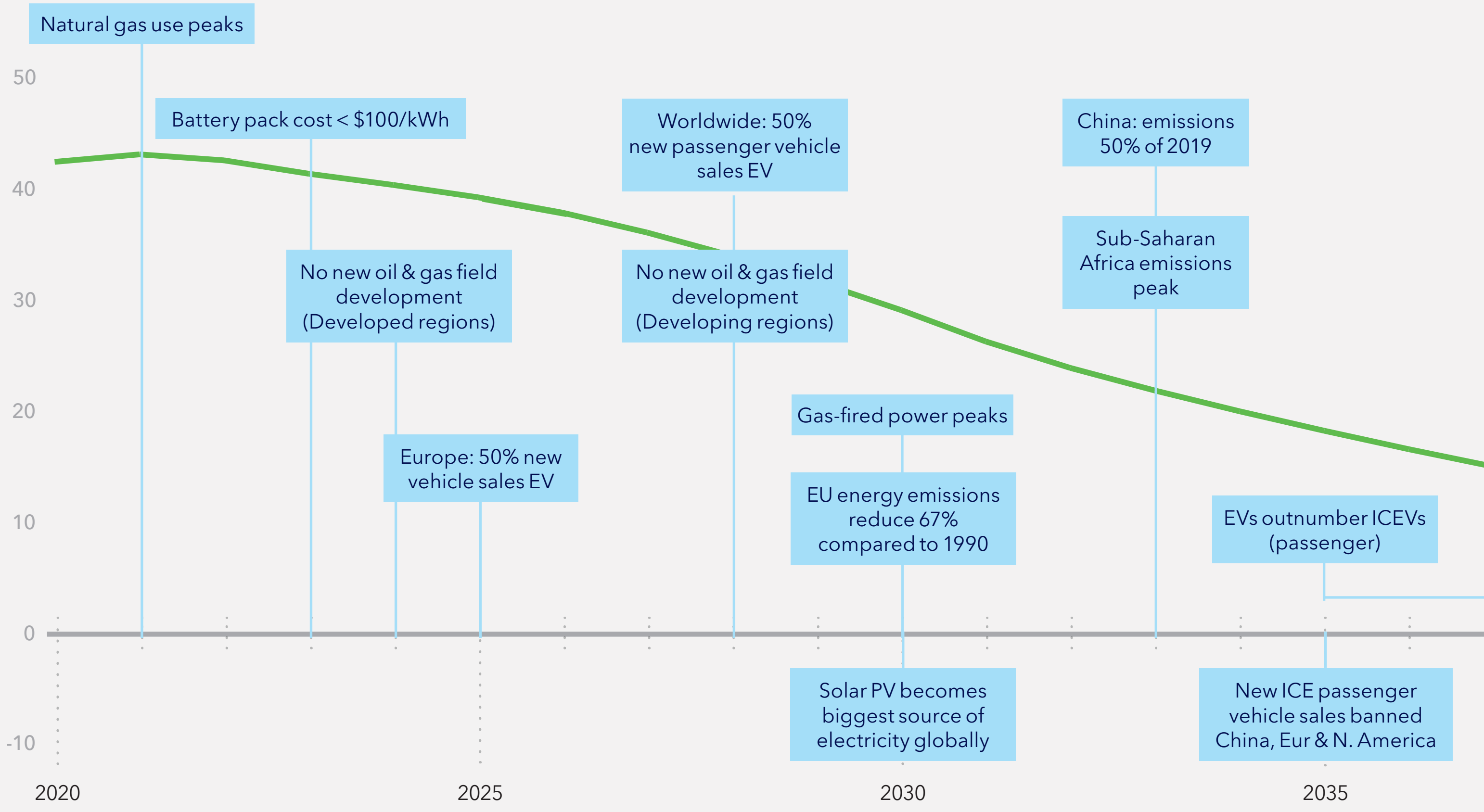
HIGHLIGHTS

Developed regions and sectors can and must go below zero emissions to reach 1.5°C on a global scale

1. **This *Pathway to Net Zero* (PNZ) is possible only with strong policy implementation, and contrasts with our 'most likely' forecast set out in our *Energy Transition Outlook* (ETO)**
   - Technically and politically feasible, but very challenging
   - Halving global CO_2 emissions by 2030 relative to 2017 is almost unattainable, and our net zero report finds emission reduction by 2030 to be 30%
   - Net zero can be achieved with scale up of today's technologies, but requires tough governmental interventions across all sectors and regions (bans, carbon pricing, mandates, and effective implementation, communication, and monitoring), and also certain behavioural shifts
   - Net zero 2050 is not an end state. In 2050, the global energy system will still be changing rapidly, delivering net negative emissions beyond 2050

Pathway to net zero emissions

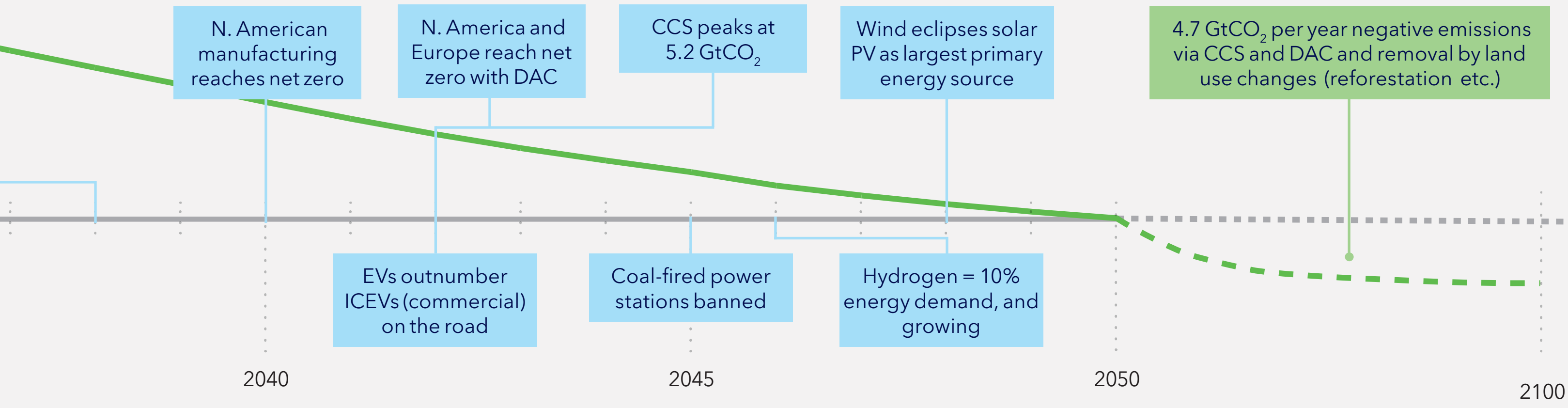
Units: $GtCO_2$/yr



2. **For the world to reach net zero emissions by 2050 and hence secure a 1.5°C future, leading regions and sectors have to go much further, faster**
   - The starting points of the world’s regions are very different, with varying emission intensities, technologies and capabilities to decarbonize
   - OECD regions need to move faster and have earlier net zero dates – in the process maturing key decarbonization technologies to spur decarbonization of less developed regions
   - North America and Europe need to reach zero emissions in 2042, while Greater China should reduce emissions by 98% by 2050
   - Some developing regions will have energy systems that are far from decarbonized by mid-century, e.g. Sub-Saharan Africa will reduce emissions by just 23% and the Indian Subcontinent by 64%
   - With hard-to-abate sectors only able to cut emissions by 80-95% at best, easy-to-electrify demand subsectors need to go below zero.

3. **Renewable electricity, hydrogen, and bioenergy are essential, but insufficient**
   - Maximizing non-fossil sources in the energy mix, as far as is feasible in 2050, delivers just 80% of the emissions reduction required for the net zero target
   - Electricity will account for 51% of energy demand, with 86% of that electricity supplied by solar PV and wind. Nuclear does not feature prominently because it is too costly compared with variable renewable energy
   - Hydrogen, predominantly green, will account for 13% of the energy demand, and dedicated renewable energy production from wind and solar plants will provide more than half of the hydrogen supply
   - Fossil fuel use reduces by 80% but will still account for 21% of the energy mix in 2050. No new oil and gas will be needed after 2024 in developed and 2028 in developing countries
   - 20% of net zero decarbonization will rely on carbon capture applied to fossil CO_2 and carbon removal, delivered through bioenergy with CCS (BECCS), direct air capture (DAC) and nature-based solutions

4. **Massive, early action is needed if we are to have any chance of reaching a 1.5 °C future**
   - Short-term action/sprints and long-term planning have to take place at the same time, starting now
   - All regions and sectors have to step up now, but the least-developed countries need dedicated technology and financial assitance to enable a fast transition
   - Technology, policies and investments need to work together – and COP26 needs to deliver a bolder, more coordinated framework for action
   - Time is the key constraint, not capital. Even with very large investments required (USD 55trn in renewables and USD 35trn in grids over 30 years) the additional costs of reaching 1.5°C are less than 1% of global GDP



1 INTRODUCTION

Despite the rapidly unfolding energy transition currently underway, DNV's *Energy Transition Outlook* (ETO) 2021 finds that the world is most likely headed towards 2.3°C of global warming by end of this century. As we emphasized, a temperature increase of that magnitude places humanity at great risk. In this report, we describe a possible pathway to avoid such an outcome. More specifically, we detail how to close the gap to net zero by 2050, by using our ETO model to develop a plausible pathway towards a future where the global average temperature increase is limited to 1.5°C by the end of the century.

1.1 FORECAST AND BACKCAST

Limiting global warming to 1.5°C is an extremely challenging task requiring, as we show, rapid reduction in greenhouse gas (GHG) emissions across all sectors and regions. This has to happen faster than anything seen historically because the costs of inaction are mounting alarmingly. Speed and scale are paramount; every tenth of a degree closer to 1.5°C makes an enormous difference – especially to vulnerable communities most affected by climate change and who, ironically, are the least responsible for emissions.

We acknowledge that there are many possible paths towards a 1.5 °C future. We have chosen to define, model and describe a pathway that is technically and politically feasible. Our pathway relies on existing technologies and their scale-up, and not on uncertain scientific and technological breakthroughs. It is politically feasible in that it relies on a proven toolbox of policy measures, and allows for developing regions to implement the necessary measures later than their developed region counterparts. 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 alternative routes to achieving a 1.5°C future, as presented by many other energy forecasters as well as by the IPCC.

In our ETO, we forecast our best estimate of the energy future; we sometimes also refer to this as the 'most likely' future. It incorporates expected economic, technological, and political developments, and leads to 2.3°C of global warming by end of this century.

In contrast, in this report, we aim for a future that limits global warming to 1.5°C by the end of this century – not through a forecast of what is likely, but through a backcast of what is necessary. This report therefore describes both a 1.5°C future and provides a pathway for closing the gap between the future we are heading towards and the future defined by the Paris Agreement (Figure 1.1). By net zero we mean that the sum of global CO_2 emissions from energy, processes and land use reaches zero by 2050.

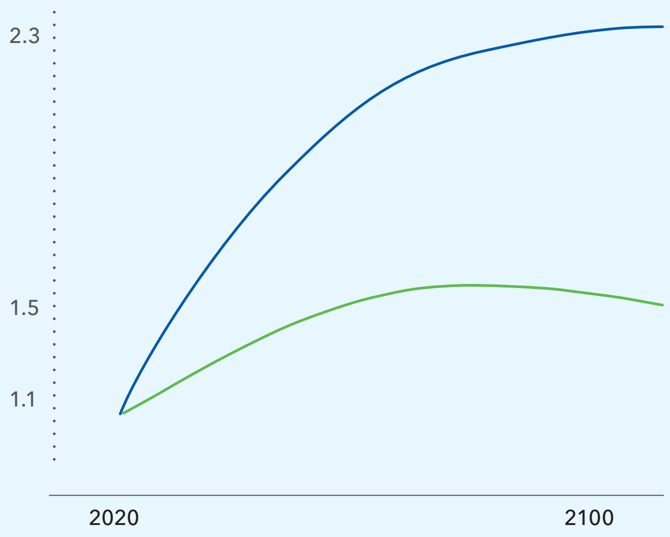
> Limiting global warming to 1.5°C is an extremely challenging task requiring, rapid reduction in greenhouse gas (GHG) emissions across all sectors and regions.

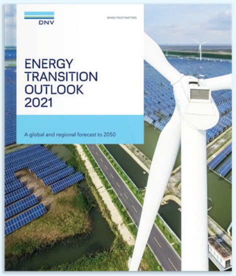
The focus of the two reports

FIGURE 1.1

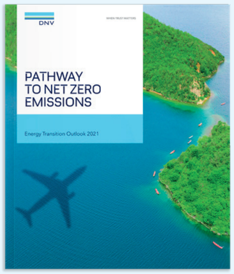
The focus of the ETO and the Pathway to net zero reports

Units: Change in average temperature wrt pre-industrial levels (°C)





ETO 2021
Most likely heading towards 2.3°C



Pathway to net zero
How to close the gap to 1.5°C

Chapter guide

Chapter 1 describes the science base underpinning our work and details our approach. It also recaps key findings from the ETO report and describes the gap that needs to be closed to attain a 1.5°C future. The chapter also outlines how we have applied various policy principles we find critical to reaching the net zero objective.

Chapter 2 details our pathway to net zero emissions (PNZ) by describing both the required emissions trajectory and how energy demand and supply sectors can contribute to achieving the pathway on a global scale. This chapter also outlines the costs and energy expenditure needed to reach a 1.5°C future. While several studies have estimated the number of jobs that could be created in the process of realizing a 1.5°C future (e.g., ILO et al., 2020), that is not something we have independently modelled for this report, although we might do so in the future.

Our PNZ comprises several roadmaps for sectors and regions, detailing how each sector and each region would contribute to reaching the PNZ.

Chapter 3 includes roadmaps for many of the largest emitting and most challenging sectors to abate, including transport subsectors such as maritime and aviation, and manufacturing subsectors such as steel and cement. The selection of sectors is non-exhaustive; there are smaller sectors not covered in this report.

Chapter 4 includes roadmaps for all ten of our world regions, as described in our ETO. This chapter is exhaustive in the sense that all countries are included as part of one of the ten regions.

Chapter 5 summarizes methane emissions and other GHG-emitting sectors outside the energy systems and highlights the actions necessary to achieve the pathway.

1.2 THE SCIENTIFIC BASIS

The Paris Agreement (2015) states: "This agreement [….] aims to [….] hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C". Three years later, the IPCC special report on 1.5°C (IPCC, 2018) highlighted that limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050, with "concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane". The report depicted 90 different pathways for how this could be achieved and highlighted four of these as "illustrative model pathways" to show a range of mitigation approaches.

Common to almost all the pathways from the IPCC, is that the net global anthropogenic CO_2 emissions in 2050 are close to zero, before moving into a "post 2050" era characterized by net negative emissions. The scientific conclusions from the IPCC paved the way for UN Secretary-General António Guterres, to state, at the end of 2020, that a top UN priority in 2021 was to build a global coalition for carbon neutrality. A long list of net zero pledges from countries and companies alike has followed.

Globally, the net zero focus makes a lot of sense. As temperature increase is closely correlated with CO_2 concentration in the atmosphere, halting global temperature increase requires global net emissions to reach zero. This is also why we find it scientifically sound to focus our methodology and this report on how, plausibly, to accomplish the very challenging task of achieving global net zero CO_2 emissions in 2050.

That net zero CO_2 emissions in 2050 will limit global warming to below 1.5°C is of course a simplification. Indeed, although CO_2 represents 65% of GHG emissions,

what happens to other highly potent greenhouse gases such as methane, will also play a significant role if we are to keep global warming below the 1.5°C threshold. The IPCC carbon budgets and net zero considerations have taken account of emissions from other GHGs. Methane emissions from fossil fuels or changes in agricultural practices, including fertilizer use or aerosol emissions, have a 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, corresponding well with the very low CO_2 emissions we project; hence the approach is consistent.

In Chapter 5, we describe how methane emissions from the energy industry contribute to global warming. Beyond the energy system, other gases such as methane from the agricultural sector are also important. We have included our views on these emissions in Section 5.3.

While net zero is a logical goal on a global scale, it should be applied with care on a regional scale or sectoral scale. 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 threshold. It is both implausible and unjust to expect all sectors, regions, or countries to achieve this challenging goal at the same time. To begin with, the starting points for each region are very different, as are their abilities to deal with emissions; similarly, the challenges facing the various demand sectors vary considerably, in terms of readily available abatement options.

In light of these considerations, this report applies the net zero approach on a global scale only, while allowing for a large differentiation on a regional scale. In a similar vein, we apply the net zero approach to the entirety of energy demand, and not at the scale of individual demand sectors, which will decarbonize at different rates. Using our most likely future from the ETO gives us the opportunity to see where regions and sectors are going to be – compared to where they need to go.

While the concept of a 'just transition' is compelling, we have not attempted to model a dramatic transfer of wealth across the world regions over the next 30 years, in part because energy provision and consumption is in itself a relatively small component of total economic activity, and in part because it is unfortunately not very likely to happen any time soon. Therefore, in our PNZ, we have applied the same population and GDP growth assumptions, and therefore also GDP/person in 2050, used in our ETO 'most likely' future. While this is not consistent 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 measures to achieve net zero relative to the GDP of the region – as further described in our policy section. Our approach is thus arguably balancing the fair and the plausible.

> Common to almost all the pathways from the IPCC, is that the net global anthropogenic CO_2 emissions in 2050 are close to zero, before moving into a "post 2050" era characterized by net negative emissions.

An alternative approach could have been to apply the individual nationally determined contributions (NDCs) from each country. While this idea from the Paris Agreement is a very good one, the overwhelming difficulty from the outset has been that the sum of pledges falls well short of the global ambition of net zero in 2050. While being aware of and informed by the NDCs, we have therefore not applied them directly, but instead have designed a pathway which, while challenging, is technically achievable and politically feasible, and which will achieve net zero emissions with the intent to limit global warming to 1.5°C.

1.3 RECAP OF OUR ETO – THE 'MOST LIKELY' FUTURE

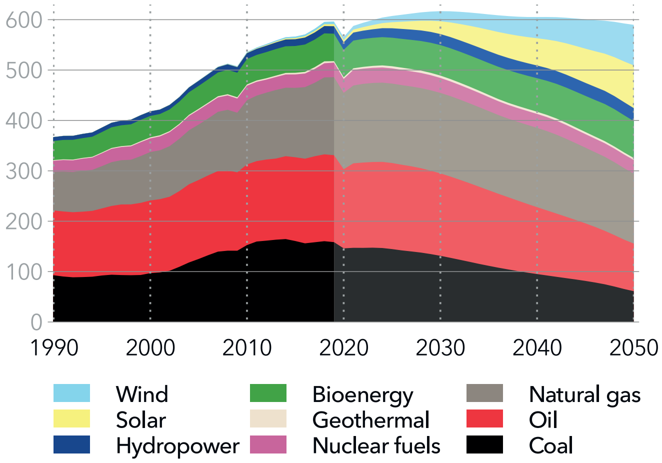
Earlier this year, DNV presented the fifth edition of its Energy Transition Outlook (ETO) – our `best estimate` forecast of the energy future which stands in contrast to scenario-based outlooks presenting multiple scenarios.

Historically, energy demand has grown in lockstep with GDP. In our best-estimate forecast of the future energy system, we predict that this is going to change dramatically in the next three decades due to accelerated electrification and dramatic efficiency gains both outpacing economic growth in the coming years. Our best estimate forecast predicts that world final energy demand will level off at some 466 EJ by around 2035, which is only 8% higher than in 2019. Thereafter, energy demand flattens through to mid-century. However, it is not a certainty that final energy demand after 2050 will remain stable. With most energy services electrified by then, energy demand might rise once again in conjunction with economic growth. Still, emissions are not likely to rise after 2050, despite the possibly higher demand for energy services. By 2050, a growing share of final energy demand will be supplied by renewables, constantly adding to primary energy supply. Their share in the primary energy supply will triple from today`s 15% to 45% by 2050, whilst the fossil share of the primary energy supply mix will fall from 80% today to 50% by then (Figure 1.2). Nuclear will be stable at 5% between today and 2050.

FIGURE 1.2

World primary energy supply by source in best estimate forecast

Units: EJ/yr



Historical data source: IEA WEB (2020)

In 2019, 29% of the world's energy demand was from transport. The sector's strong reliance on oil (92% in 2019) will shrink to 60% towards 2050 due to a growing share of electricity and hydrogen used in all forms of transport. The demand share of the buildings sector (28%) was very close to that of transport in 2019. Despite a rapid growth in both residential and commercial floor area, energy demand from the buildings sector will grow by only 26%, reaching a 33% share of total demand by 2050 due to significant energy efficiency gains linked to a decline in the cost of energy-efficient technologies, and advances in 'green' building design and construction. In 2019, 30% of the world's final energy demand was consumed by the manufacturing sector with the base-materials subsector taking the largest share within manufacturing (38%). Manufacturing's final energy demand will grow by 8% to mid-century with an associated fuel mix change. Coal's share will continue to decline from today's 35% to 20% by 2050, with electricity and hydrogen filling the gap, contributing to the average 1.6% efficiency improvement in the manufacturing sector over the next three decades.

The ongoing energy transition is characterized by the growing dominance of electricity in final energy demand with its share growing from today's 19% to 38% by mid-century owing to a combination of declining costs, technological progress and favourable decarbonization policies. At the same time, direct use of oil and coal will halve by 2050, while shares of direct use of gas, bioenergy and heat stay stable. Hydrogen's share will grow from negligible levels today to 5% by 2050. The majority of this is going to be used for industrial heating (30%), with smaller shares used in maritime transport (16%), heavy long-haul trucking (6%), aviation (12%), and in buildings (9%). The remaining third is going to be used in non-energy uses. By 2050, global renewable sources will have a 60% share, dominated by hydrogen production from electrolysis powered by dedicated wind and solar PV generation. Wind and solar PV will also dominate electricity production by mid-century. 82% of the world's grid-connected electricity production will originate from renewable sources with wind (33%) and solar PV (36%) having the highest shares, leaving little space for fossil-based electricity production, though in some regions such as the Middle East and North Africa and North East Eurasia, fossil fuels in power supply remain central.

Although the aforementioned developments require massive investments in capital-intensive renewables and associated networks, the share of global GDP allocated to expenditure on energy will decline steadily from 3.2% today to 1.6% by mid-century.

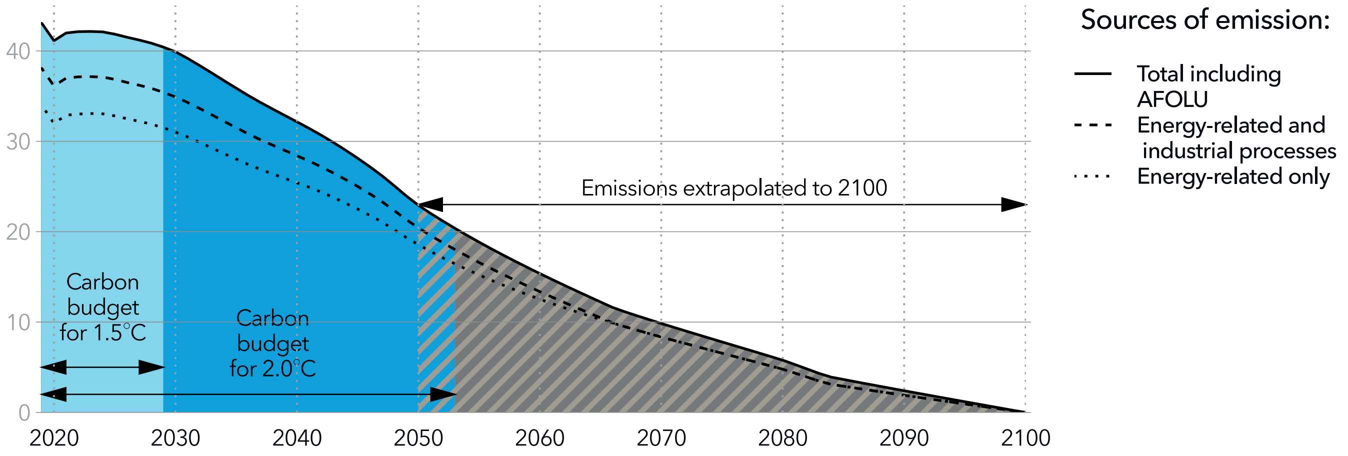
Global energy-related CO_2 emissions associated with our ETO forecast are expected to be 18.6 Gt CO_2 in 2050, a 45% reduction compared with current levels. Although significant, this is far from the Paris Agreement ambitions to halve greenhouse gas emissions (GHG) by 2030 and achieve net zero by 2050. According to our best estimate forecast, by 2050 the largest contributor to these emission levels is the manufacturing sector (6 Gt CO_2), followed by transport (5.4 Gt CO_2) and buildings (4.8 Gt CO_2). Carbon capture and storage (CCS) uptake will accelerate in the 2040s, capturing about 1.3 Gt CO_2 emissions from power, manufacturing, process-based emissions and natural gas-based hydrogen production. Our ETO shows how each ten world regions have very different starting points and thus different emission reduction pathways to 2050. The Indian Subcontinent and Sub-Saharan Africa will increase their emissions between 2019 and 2050 by 40% and 55% respectively, whereas OECD regions will reduce their emissions by about 70% each.

With our best estimate forecast of the future energy system and an extrapolation of emission trends in non-energy sectors, the 1.5°C budget will be exhausted by 2029, and the 2°C budget shortly after 2050. In the ETO, a net zero emissions economy would likely only be reached around 2100. In the absence of the major interventions outlined in this report, the world's future energy system is certainly not on track to meet the goals of the Paris Agreement.

FIGURE 1.3

Carbon emissions and carbon budget according to best estimate forecast Energy Transition Outlook

Units: $GtCO_2$/yr



1.4 THE GAP TO BE CLOSED

As described in Section 1.2, "The Scientific Basis", the IPCC has defined the pathway consistent with a 1.5 °C future as requiring net zero CO_2 emissions by 2050. The ETO forecast, summarised in the previous section, shows 22.9 Gt annual CO_2 emissions by 2050. Simply put, the absolute gap to be closed is therefore 22.9 Gt CO_2 in 2050.

Knowing that global temperature increase is closely correlated with CO_2 concentration in the atmosphere, cumulative emissions are at least as relevant as the absolute emissions in any given year. In 2020, the remaining carbon budget for 1.5°C using the p67 threshold was 400 Gt CO_2 (IPCC, 2021a). In our ETO, the 1.5°C cumulative carbon budget overshoot was calculated to be 690 Gt of CO_2 by 2050, and roughly estimated to be 1.250 Gt of CO_2 by 2100, as illustrated in Figure 1.4. This, therefore, is the likely overshoot of the 1.5°C carbon budget derived from our ETO forecast.

A key question is – how do we close this gap?

Physically, the gap will be closed through implementation of low-emission technologies. There are technical solutions that need massive deployment and scale up, such as renewable energy, storage, grids, hydrogen, and CCS. Other technologies must be scaled down, such as coal, oil, gas, and combustion engines.

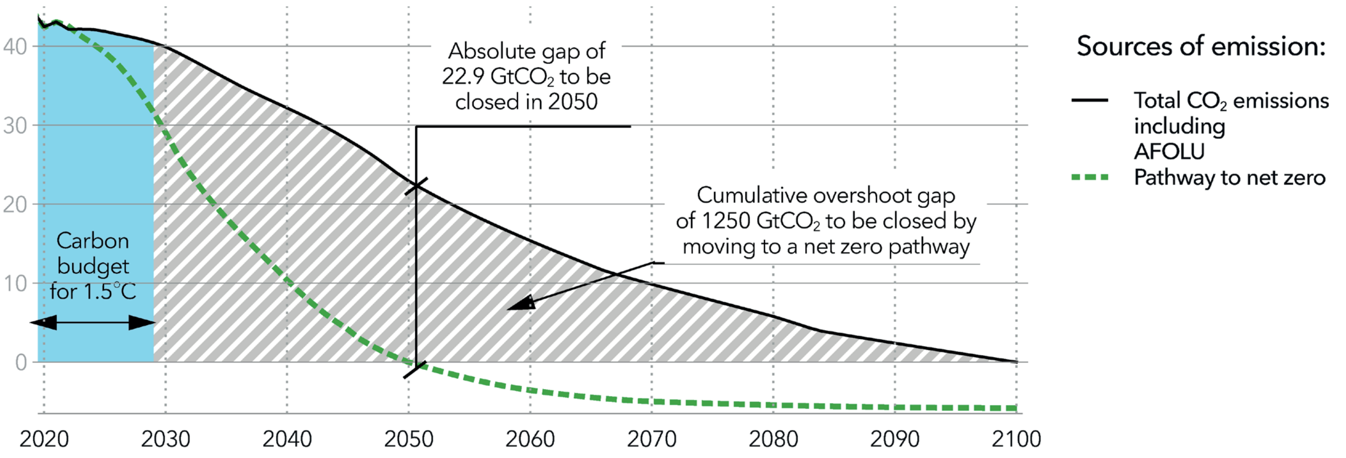
The main lever for scaling up abatement solutions, both in terms of their development and implementation, however, is policy. If we are to close the gap and limit the global average temperature increase to 1.5°C, it will be through tightening energy, industrial and climate policies in all regions and sectors, and by applying the entire policy toolbox. The net zero policy considerations included in the PNZ, are described in the next section.

The emissions reduction potential from changes in behaviour is also interesting. Behaviours are nudged by policies, and whether behavioural changes are encouraged or enforced involves a fine balance. One example is that in aviation, we have limited the increase in the number of flights by making flying more expensive through significant sustainable aviation fuel (SAF) uptake policies, such as taxes and mandates.

FIGURE 1.4

CO_2 emissions and carbon budgets (Energy Transition Outlook) and Pathway to Net Zero

Units: $GtCO_2/yr$



But even the 1.5°C net zero emission pathway will have a gap to close after 2050.

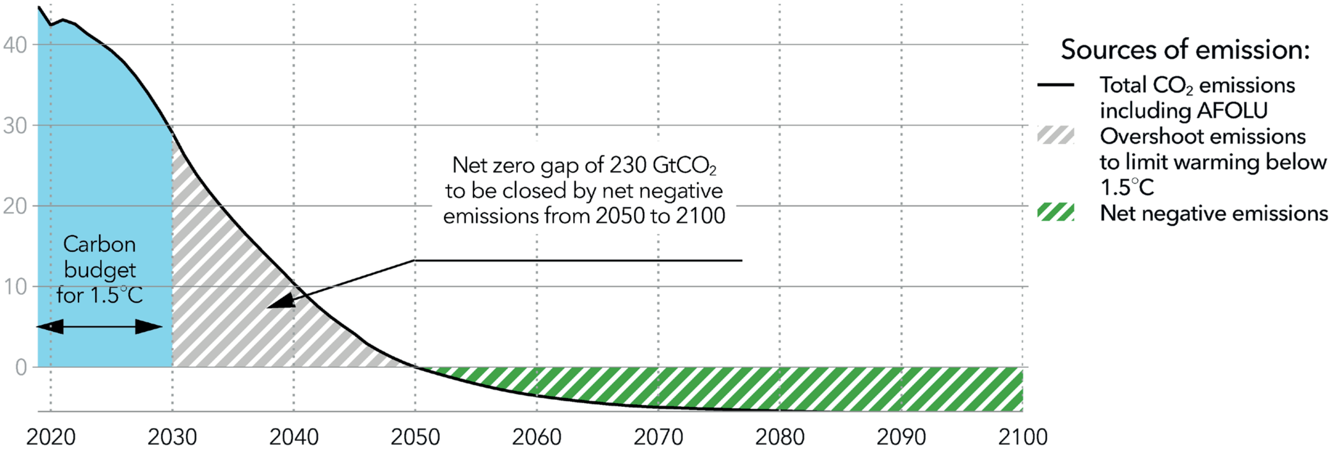
IPCC (2021a) emphasises that even the most optimistic SSP1-1.9 scenario holding global warming below 1.5°C will have a temporary overshoot of the 1.5°C carbon budget. Indeed, our PNZ finds the same, and as described in the pathway results in Chapter 2, the likely 2050 overshoot will be 230 Gt of CO_2. This is a gap in the 1.5°C pathway that needs to be closed with net negative emissions *after* 2050. In the 50 years through to 2100, average net negative emissions therefore need to be 4.7 Gt/yr to produce 230 Gt in net negative emissions.

> If we are to close the gap and limit the global temperature increase to 1.5°C, it will be through tightening energy, industrial and climate policies in all regions and sectors.

FIGURE 1.5

Closing the overshoot gap in the pathway to net zero emissions

Units: $GtCO_2$/yr



1.5 NET ZERO POLICIES

For the energy transition to achieve net zero emissions, DNV anticipates an intensification of policy efforts to implement emission abatement options at massive scale and speed. Strengthening of both requirements and incentives to advance decarbonization across all sectors and regions is inevitable.

In DNV's *Energy Transition Outlook 2021,* we described in detail what we term a "policy toolbox" and how our forecast factors in policy measures (Figure 1.6) that propel energy system evolution in three main areas:

- **Supporting technology development** and activating market uptake that closes the profitability gap for clean energy technologies competing with existing technologies
- **Restricting the use of inefficient or polluting products/ technologies** by means of technology requirements or standards
- **Providing economic signals** to reduce carbon-intensive behaviours.

DNV's PNZ activates the policy toolbox of proven policy measures, in both demand and supply sectors.

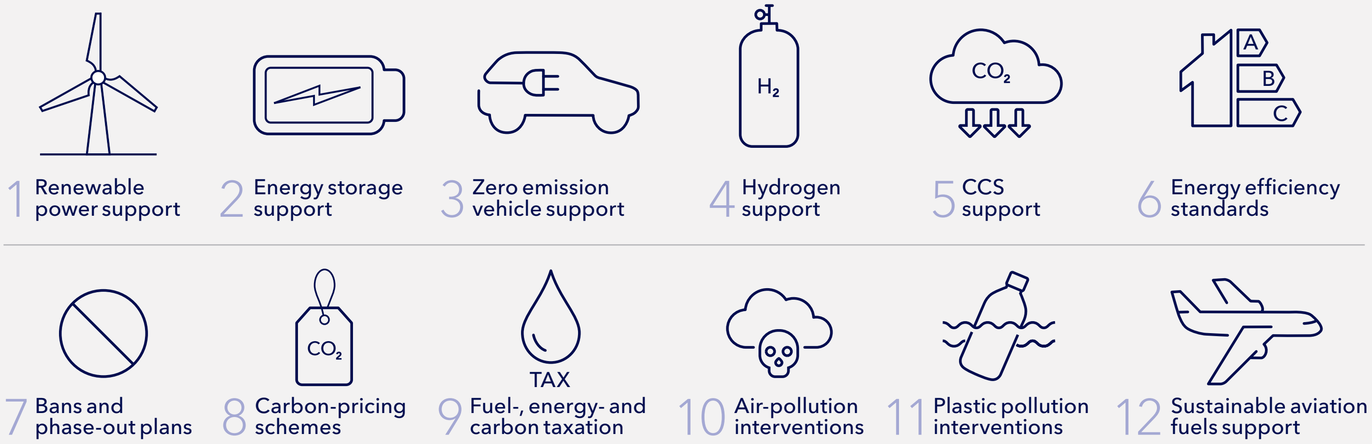
The overarching principle guiding our policy analysis, and implementation of policy measures, is that we expect high GDP regions (Europe, North America, OECD Pacific, Greater China) to move at faster pace and greater depth to meet the Paris Agreement. These regional economies have strong decarbonization goals, account for the bulk of emissions (historically and presently above 60% of global emissions), and emit far more than less affluent regions. They also possess the wealth and competence for technology development and to boost cost learning curve-based cost reductions for key abatement technologies.

At the level of sectors or supply chains, comprising several technologies at varying levels of commercial readiness, a blend of policies will be needed. The urgency of achieving net zero will require synchronous acceleration of both technology development and uptake.

Here, we highlight the strengthened policy factors forging our pathway to net zero, and more detail is presented in Chapters 3 and 4 on sectors and regions respectively.

FIGURE 1.6

Policy factors included in our Outlook



Buildings

- Bans target phase-out of fossil-based heating and limit equipment choices for space/water/cooking
- Higher energy efficiency standards for new builds and renovations to reduce heating/cooling demand
- Consumer-side fossil-fuel subsidies are removed, and higher cost of capital hinders fossil-based heating

Transport

- Fuel economy emission standards tighten in all markets, and taxes on gasoline and diesel increase
- Bans on new ICE vehicle sales in developed regions from 2030 (first-mover countries and stepwise regional implementation), followed by most developing regions in the 2040s
- Zero-emission vehicle incentives promote e.g., EV adoption and support incl. charging infrastructure
- Shipping and aviation fuel-mix shifts driven by fuel blending mandates and carbon pricing

Manufacturing

- Carbon pricing drives CCS uptake
- Energy intensity improvements driven by regionally differentiated taxation on fuels
- Cost of capital increases drive down attractiveness of fossil-based equipment
- Requirements increase material efficiency and recycling rates (e.g., plastics, scrap steel)
- CAPEX support for electrification and for hydrogen in iron and steel-making
- Energy taxation encourages fuel switching from fossil fuels to electricity and hydrogen usage

Power generation

- Net zero pledges trigger cost of capital increases that reduce the attractiveness of fossil-based generation
- A mix of mandates and carbon pricing end unabated gas-fired generation in all regions
- Bans enable oil and coal-fired generation phase-out in all regions by 2045
- All region governments support renewable build-out, e.g., clean capacity auctions, investment subsidies for storage capacity coupled with renewable generation, and evolving market design

CCS & Direct air capture

- Higher carbon prices accelerate deployment
- Mandates require CCS in natural gas-fired power generation
- CCS and direct air capture (DAC) capacity ramp-up is enabled by policies supporting CAPEX reduction and value chain/infrastructure development

Hydrogen support

- Policy measures stimulate demand for hydrogen, such as mandates in aviation and maritime, energy taxation boosting fuel switching in manufacturing and in other hard-to-abate sectors, where hydrogen is the most viable option in decarbonization plans/obligations
- Policy measures stimulate the supply of green hydrogen, such as CAPEX support to integrated renewable electricity and electrolyser projects, subsidies to grid-powered, renewables-based electrolysis, and to supply-chain shifts in steel production

Energy efficiency

- Targets and legislation accelerate the pace of improvement in energy efficiency e.g., tightened standards for equipment and appliances, building codes, requirements renovation/retrofits, and energy intensity improvements in buildings
- Incentives to replenish equipment base (e.g., fossil-based to electricity-based technologies or switching to alternative combustion-based fuel)
- Tax cuts, access to cheap financing, and direct subsidies for energy efficient technologies
- R&D support for new technologies
- Public spending for build-out of support infrastructure, e.g., EV chargers, hydrogen, and district heating networks

Carbon pricing

- Net zero policy passes the cost of emitting to emitters and carbon prices will become more effective. High GDP regions accustomed to energy fees, will be frontrunners in carbon pricing (EUR, NAM, OPA slightly above CHN), reaching price levels of USD 100-150 /tCO_2 by 2030. By 2050, regional trajectories range between USD 50-250/tCO_2.
- Carbon-border adjustment mechanisms drive convergence among leading regions, and all regions' carbon-price trajectories are pulled upwards for effective emission cuts

Government funding & cost of capital

- Most region governments will redirect funding towards emissions reduction and clean energy, both domestic and overseas. Examples of the latter are Japan, South Korea, China announcing an end to financing and building new coal-fired power plants, and G7 countries ending support without co-located CCS
- Revision of government funding parallels a finance sector shift to align investment practices with net zero. Increasingly limited pools of capital will be available for fossil-fuel projects and with higher cost of capital, coal-fired facilities facing the highest discount rate

2 PATHWAY TO NET ZERO (PNZ)

In order to achieve net zero emissions in 2050, fossil fuel use is reduced about 80% from today, and carbon capture and removal removes a further 8 Gt of CO_2 emissions. The 2050 PNZ energy system will be dominated by solar and wind generated electricity, but also sees a strong role for hydrogen in the hard-to-abate sectors.

2.1 CO_2 EMISSIONS

The pathway to net zero emissions (PNZ) is designed so that global CO_2 emissions in 2050 hit net zero. The present (2019) emissions are 44 Gt, and our ETO forecasts 2050 emissions to 23 Gt. The levers to bring down emissions are described under Net zero policies in Chapter 1.

As illustrated in Figure 2.1, the sector with the largest emissions in 2050 is the transport sector, even though the sector reduces more than 80% of its emissions, from 8.9 Gt today to 1.7 Gt in 2050. The transport sector uses most of the world's oil, and carbon capture is very challenging. Continued use of fossil-fuelled vehicles in the road sector in the developing regions, and in aviation, make up the bigger share of the remaining 2050 transport emissions.

Today, electricity generation is the sector with the largest emissions, but also the easiest to transform into a non-fossil energy mix, reducing emissions significantly to 0.1 Gt in 2050.

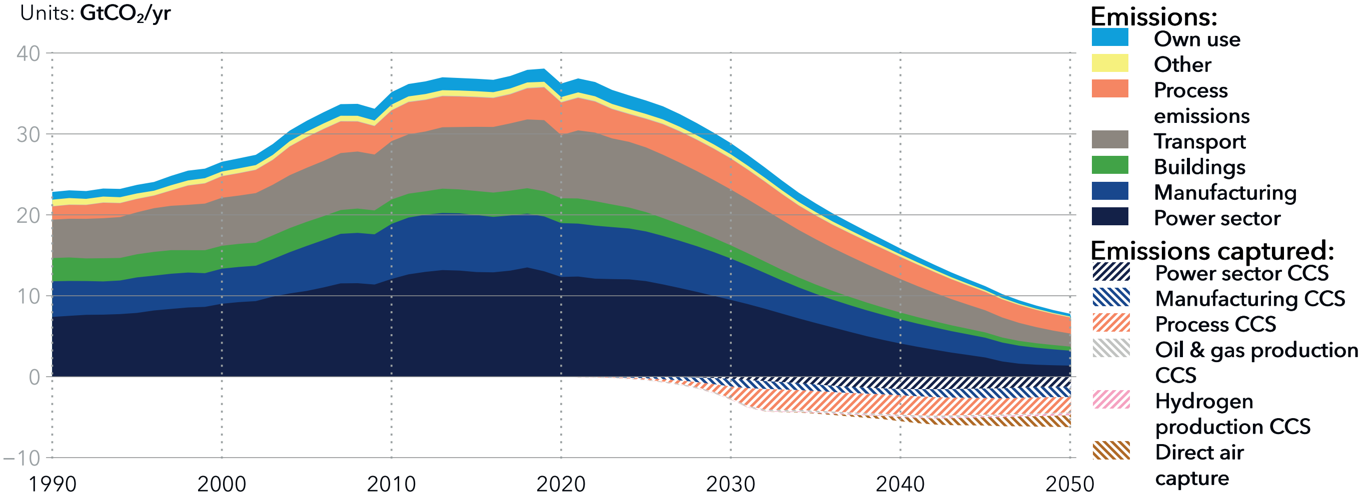
In addition to what is shown in Figure 2.1, there are emissions from agriculture, forestry and other land use (AFOLU), which will reduce from 6 Gt today to negative emissions of 2.1 Gt in 2050, as described in Section 5.2.

Further details on the various sectors and subsectors are included in the regional roadmaps in Chapter 4 of this report.

FIGURE 2.1

World CO_2 emissions excl land use by sector

Units: $GtCO_2/yr$



Fossil fuel-related emissions are currently split 38% from coal, 28% oil, 22% gas, with 11% from process emissions, and 1% from biomass.

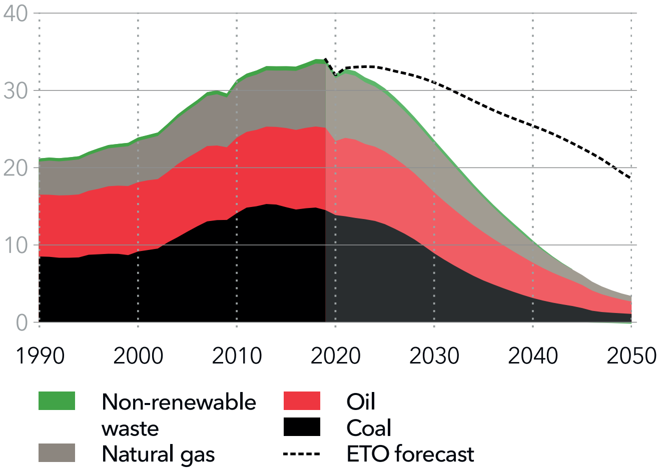
The development of emissions is well correlated with future energy from fossil-fuel carriers, but carbon capture and storage also plays a decisive role. Coal and oil use falls rapidly in our PNZ, while gas has a steady but more moderate decline. Capture rates are higher for coal and gas, where much of the CO_2 is emitted at large point sources compared with oil, with its typically small point sources. From today to 2050, coal emissions are reduced by 92%, gas emissions by 83% and oil emissions by 85%.

The 2050 emissions are relevant in themselves, but it is the cumulative emissions that decides the CO_2 concentration in the atmosphere, and hence the global climate response in terms of global average temperature increase. Cumulative emissions from 2020 to 2050 are calculated to 630 Gt in our PNZ. Comparing that to a 1.5°C carbon budget of 400 Gt, we therefore have an overshoot of the 1.5°C carbon budget of 230 Gt in 2050. This is described in more detail in Chapter 1.

FIGURE 2.2

World energy-related CO_2 emissions by energy carrier

Units:$GtCO_2$/yr



The 2050 emissions are relevant in themselves, but it is the cumulative emissions that decides the CO_2 concentration in the atmosphere, and hence the global climate response in terms of global average temperature increase.

2.2 ENERGY DEMAND AND SUPPLY

This section outlines energy demand and supply developments associated with our PNZ. Historically global energy use has grown in lockstep with population and economic activity. This trend is now decoupling, and we will see global energy demand and supply starting to decline despite a growing population and increased economic activity. This decoupling trend will intensify under our PNZ.

The population in the various regions are the same in the PNZ as in the ETO. We are using input from Wittgenstein Centre for Demography and Global Human Capital, expecting a global population of 9.4 Bn people in 2050, and peak population soon thereafter.

The global economy will continue to grow, and DNV has designed a separate model for economic growth. On average, over the next 30 years, we expect a CAGR of 2.4%, accumulating to a 100% growth until 2050, with the global economy then at USD 290trn. This growth trend is incorporated into our PNZ.

Details of our population and GDP estimates are given in the ETO. While these population and economic estimates remain the same for both our ETO forecast and our PNZ, energy demand and supply differs substantially, as we explain below.

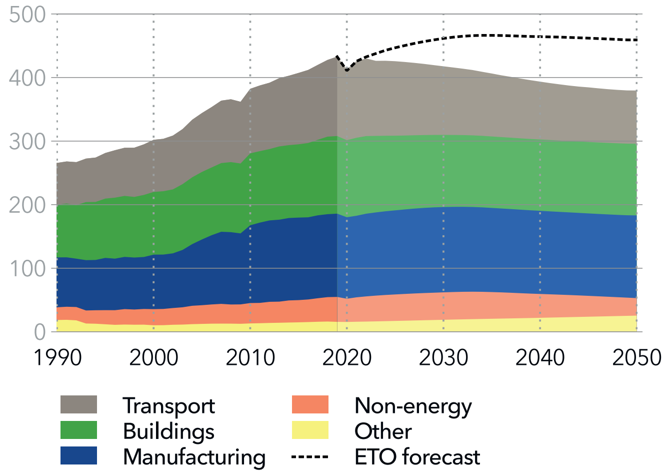
Final energy demand in the PNZ, as illustrated in Figure 2.3 is 380 EJ in 2050, a 12% decline compared with 2019. After the COVID-19 rebound in 2021 and 2022, final energy demand gradually starts reducing when our PNZ policies and technologies start to take hold. As with ETO, the manufacturing sector has the highest demand (130 EJ) in 2050 in our PNZ, and this energy use also stays flat. Building energy demand declines somewhat, and transport energy demand sees a significant decline. The stable and declining energy use does not mean we will have fewer energy services. On the contrary, the PNZ effectively leverages the benefits of energy efficiency and electrification to meet energy service needs of the population. A more detailed description of energy demand is given in the various sectoral roadmaps in Chapter 3.

Primary energy supply in 2050 in the PNZ will be very different to 2019, as is to be expected. From a value of

FIGURE 2.3

Final energy demand by sector

Units: EJ/yr

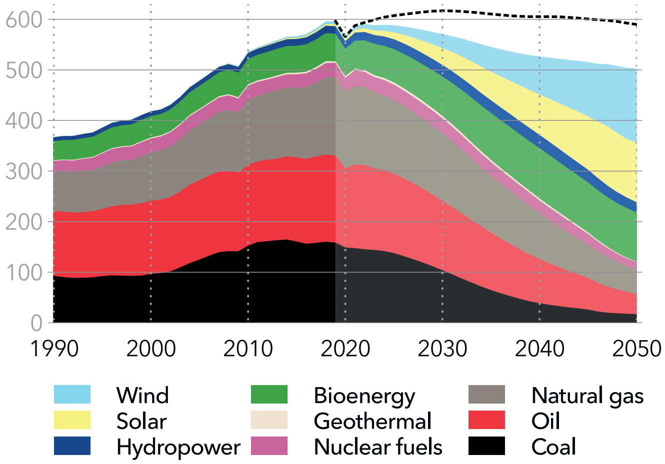


Historical data source: IEA WEB (2020)

FIGURE 2.4

Primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast. Historical data source: IEA WEB (2020)

596 EJ in 2019, the primary energy supply drops to 503 EJ, a reduction of 16%, as illustrated in Figure 2.4. This contrasts with our ETO estimate of hardly any reduction in 2050 compared with 2019. While our assumptions regarding population and GDP have not changed, this clearly indicates that the PNZ will also be a more 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. In our PNZ, world primary energy supply has already peaked in 2019.

Fundamental to achieving our PNZ, is a massive ramping up of variable renewable energy sources (VRES) accompanied by a drastic near phase-out of coal and strong decline of the other fossil fuels. Solar and wind together provide more than half of primary energy supply. With continued high learning rates, there is a 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.

Coal is nearly phased out in our PNZ but is still used mainly for manufacturing uses in regions such as Sub-Saharan Africa (SSA) and the Indian Subcontinent (IND), which have transitions lagging the developed regions, with a later phase-out of coal.

Despite the push to eliminate unabated fossil fuels completely, oil (8%) still persists in the energy system in 2050, due to its prevalence in hard-to-abate sectors such as aviation and continued, but limited, use in the road sector in developing countries where charging infrastructure will not be 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 remain with 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.

Bioenergy increases its share and role in our PNZ, growing from a 9% share in 2019 to a 19% share in 2050. This is due to multiple factors: heat-only plants having to use bioenergy; the increased use of bioenergy in the manufacturing sector; and the use of bioenergy for production of biofuels, especially for aviation and maritime sectors. Regulations and mandates aim to replace natural gas with emission friendly biomethane where this is possible and available.

Both nuclear and hydropower have a continued presence in the energy system in our PNZ. Because of its stable and dispatchable electricity, and its long lifetime, hydropower will still play a role in the energy mix, and its share increases slightly from 2% in 2019 to 4% by 2050. Surprisingly, while nuclear still maintains a presence in 2050, its importance reduces from 5% in 2019 to 3% in 2050, because it loses out to rapidly declining costs and uptake of solar and wind.

Coal

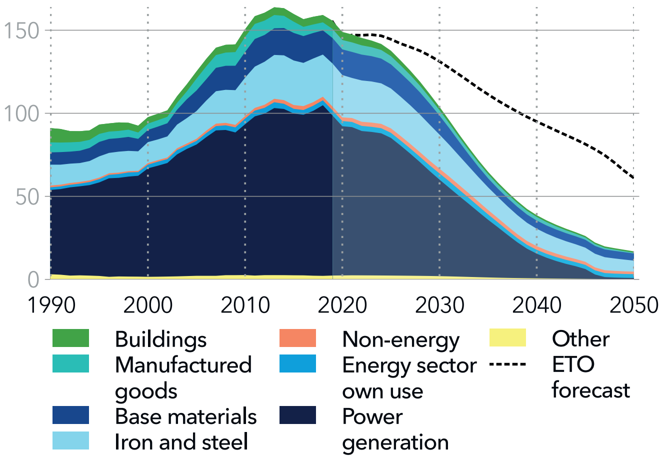
Owing to its high emissions intensity, coal is the first target of decarbonization policies. Global demand in the PNZ will plummet, already decreasing by 33% in 2030, and falling 89% by 2050.

The power sector will show the most impressive transformation. Representing 96 EJ and almost two thirds of coal demand in 2019, a fast and global transition will lead to a 39% decrease in demand by 2030, 77% by 2040 and a complete phase-out by 2050 due to a global ban of unabated coal use by then.

FIGURE 2.5

World coal demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2020), US DOE (2010), Heat Roadmap Europe (2015)

For high-heat processes in the manufacturing sector, coal's phase-out will be more tempered despite its high carbon emissions. In iron and steel, coal use will decrease by 20% by 2030 and 74% by 2050 compared with 2019 levels, for both industrial heat and iron ore reduction. A similar decline of 72% over the 2019-2050 period will be observed for base materials. The Indian Subcontinent (IND) and South East Asia (SEA) regions will be driving 77% of the remaining use in manufacturing by 2050, with use even continuing to increase in these regions until the mid-2030s.

Around 800 million tonnes of coal will still have to be extracted by 2050, exclusively as hard coal adapted for use in industry. The biggest producers – mostly meeting their own demand – will at that time be the Indian Subcontinent (49% of global production), Greater China (14%), Sub-Saharan Africa (14%) and North East Eurasia (11%).

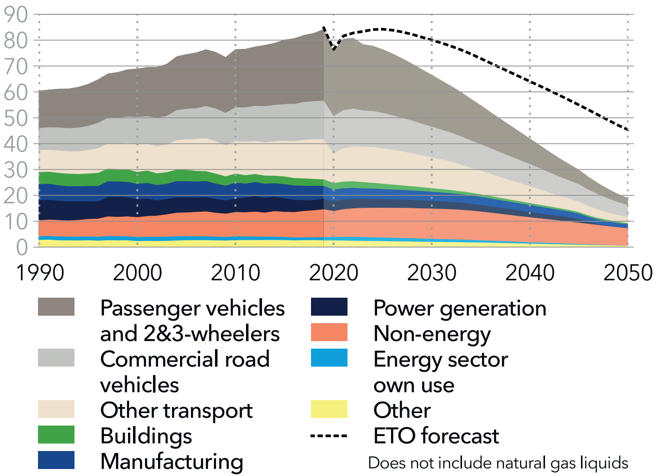
Oil

Global oil demand in our PNZ will fall 77% from 165 EJ in 2019 to 38 EJ in 2050. After the 2021 and 2022 rebound from the pandemic, the decline starts already in 2023, and by 2030, global oil demand will be 21% lower than in 2019.

FIGURE 2.6

World oil demand by sector

Units: Mb/d



Does not include natural gas liquids
Historical data source: IEA WEB (2020)

Looking at demand sectors, we find that oil use in the transport sector, currently accounting for more than two thirds of global oil use, will reduce more than 80% over the next three decades, owing to electrification of road transport as well as hydrogen-based fuels replacing oil in aviation and maritime transport.

The second biggest sector, non-energy use of oil in plastics and petrochemicals, is the sector where oil demand keeps up reasonably well. As this oil is not burned and does not cause direct emissions, it is also the only sector where oil demand is equal between our PNZ and our ETO. However, unlike most other forecasters, DNV expects oil use to peak in the non-energy sector and decline towards 2050, owing to increased recycling in the petrochemical and plastics industry.

In a world with rapidly declining oil demand, oil production will be increasingly concentrated in the region with the lowest production cost: Middle East and North Africa (MEA). As we move towards 2050, this region will dominate oil production. Indeed, in our PNZ analysis, three quarters of all oil production will come from MEA in 2050. It should be emphasized that the regional spread of production is uncertain as supply-side policies to control production, in an oversupplied, shrinking market, have yet to be agreed among hydrocarbon producing countries, and this is unknown and unfamiliar territory for the oil industry.

Nevertheless, in our PNZ, there is virtually no need for new oil to cover global oil demand. The pathway has a short period where new oil capacity additions fall rapidly from 2022 towards zero in 2024 in developed regions and 2028 in developing regions, with no new oil additions needed thereafter.

Gas

In our PNZ, global gas demand is expected to decline consistently from 163 EJ today to 142 EJ by 2030 and fall further to 73 EJ by mid-century, giving an overall decline of 55% in global demand over the next three decades. In terms of the sector breakdown, the power sector will remain the primary consumer of gas, contributing 58 EJ to total demand today, up to 60 EJ in 2030, and falling to 24 EJ by 2050. While continuing to be the largest sector, the share of the power sector will decline slightly from 36% today to 33% by 2050.

The building sector, currently consuming the second-largest share of global gas at 21%, will, as a result of increasing electrification of building heating and cooking, drop to 8% and fifth position among gas-using sectors by 2050. As in the case of oil, non-energy use of gas as a feedstock, on the other hand, will climb from fifth (9%) to second position (16%) since it is not a major emitting sector. Energy sector's own use will decline slowly from 21 EJ today to 12 EJ by 2050, and manufacturing sector energy demand will more than halve from 26 EJ today to 11 EJ by mid-century.

North America (NAM), currently the world's leading producer of natural gas responsible for a quarter of global production, will concede this position to North East Eurasia (NEE), with less stringent climate ambitions as well as lower extraction costs. By 2050, NEE will dominate the natural gas market, supplying close to half (47%) of the world's demand (while NAM's share is expected to go down to 8%). The MEA region will maintain its second-place position, supplying on average 18% (between 15% and 19%) of global gas over the next three decades.

Before the end of this decade no new capacity additions will be required to respond to global gas demand, and as such, new capacity additions are forced to stop within this decade worldwide. They will be rapidly phased out from 2022 to 2024 in OECD regions and from 2026 to 2028 elsewhere in the world. That is not a challenge from a supply point of view ; the existing fields' supply of gas is sufficient to meet all future demand.

Solar PV

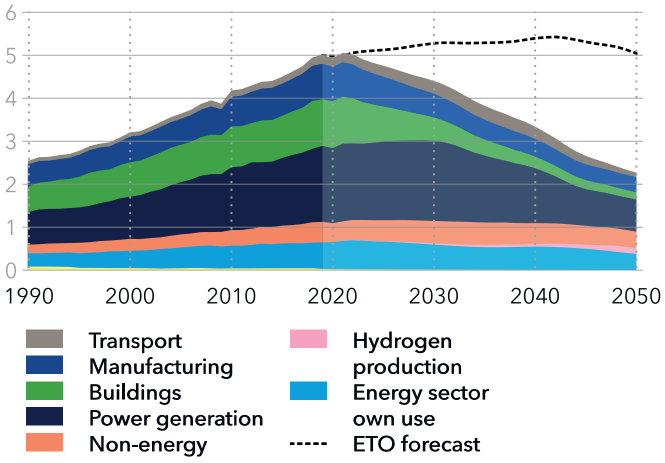
Together with wind, solar PV is already the cheapest generator of new electricity in most places in the world, and costs continue to fall rapidly. The present share of 3.2% of global electricity generation in 2020 is however modest, but the rate of increase is stunning. In the PNZ, we see a near tenfold growth of grid-connected solar PV from 0.9 in 2020 to 8 PWh in 2030. The strong growth continues, reaching 29 PWh in 2050. By 2030, solar PV will take over as the largest source of electricity globally, a position it will hold until 2048, when wind becomes the largest source of grid-connected power supply. In 2050, solar PV will produce 41% of the world's grid-connected power, trailing wind's 43%.

As shown in Figure 2.8, the growth will initially be dominated by Greater China (CHN), which will grow its share

FIGURE 2.7

World gas demand by sector

Units: Tm^3/yr

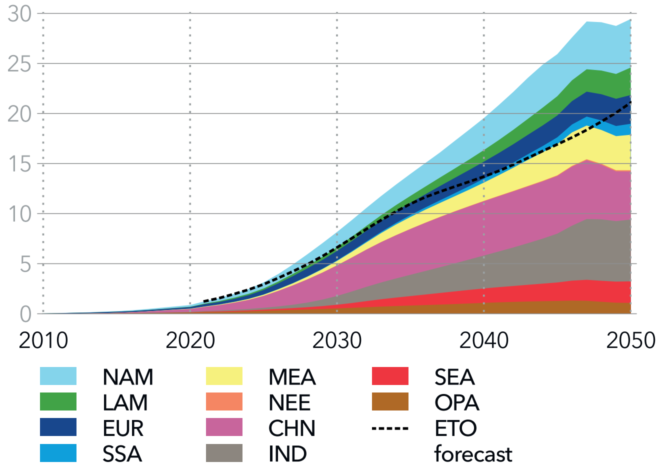


Includes natural gas liquids and biomethane. Historical data source: IEA WEB (2020)

FIGURE 2.8

World solar PV generation by region

Units: PWh/yr



Historical data source: IEA WEB (2020), GlobalData (2021) from the present 31% to 38 % of all installed solar PV in 2028. Although CHN will continue to grow thereafter, the strongest growth after 2030 will be in the Indian Subcontinent (IND) which, in 2050, will hold the largest share with 21% of world's grid-connected solar. We will see a strong solar PV build-out in all regions with the exception of North East Eurasia (NEE).

In addition to the grid-connected capacity, we will have a moderate solar PV off-grid production of 2.8 PWh in 2050, with integrated renewable electricity and electrolyser projects for dedicated hydrogen production – corresponding to 10% of the grid-connected PV production. The PV off-grid production for hydrogen will be biggest in the Indian Subcontinent (IND), followed by North America (NAM).

Finally, there will be a small amount (0.1 PWh) of off-grid production, mainly in Sub-Saharan Africa (SSA) and some in the IND region, supplying off-grid power to rural districts for lighting, mobile charging and other small end uses.

It is a massive task to grow solar PV at the speed envisioned in the PNZ. PV capacity installations – for grid and off-grid combined – are growing from the present 100+GW per year to around 630 GW per year in 2030 and then staying at that level until 2045, as shown in Figure 2.9. The model shows a spike in installations, of up to 2500 GW per year in the late 2040s, which is a result of a coal ban in the power sector in the 2040s.

Total PV installed is 24 TW in 2050, of which 14 TW are pure solar and 10 TW are solar + storage. CHN will be the biggest region with 5 TW installed, followed by IND with 4.5 TW and NAM with 3.5 TW. For IND, these large amounts of solar PV pose a challenge from a space (land use) perspective, requiring some 80,000 square kilometres for PV installations. Although deemed doable, this will require careful planning.

Wind

Electricity from wind undergoes remarkable growth in the PNZ, moving from 5% of the electricity generation in 2019 to 18% in 2030, 31% in 2040 and finally accounting for 45% in 2050. We consider three categories of wind power plants: onshore wind, fixed offshore wind, and floating offshore wind. Of these three, onshore wind power grows 16 times from 2019 to 2050. In comparison, fixed offshore grows 8 times more than onshore wind but from a much lower base, and accounts for 14% of the total electricity generation by 2050. Of the three, floating offshore wind is the least mature and has the lowest share in electricity generation (2.5%) in 2050. Globally, by 2050 the power

FIGURE 2.9

World Solar PV gross capacity additions

Units: TW/yr

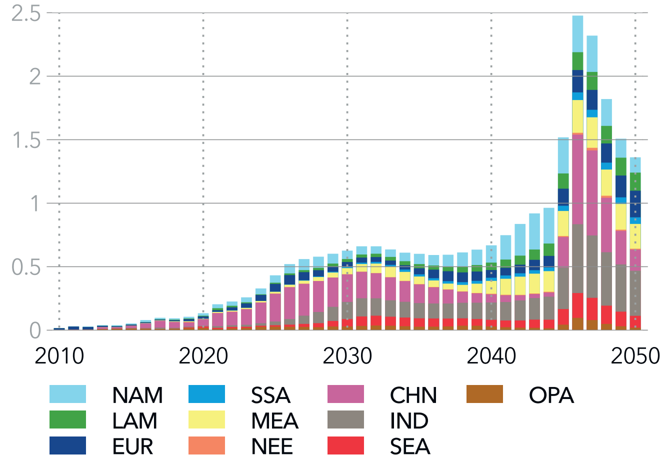
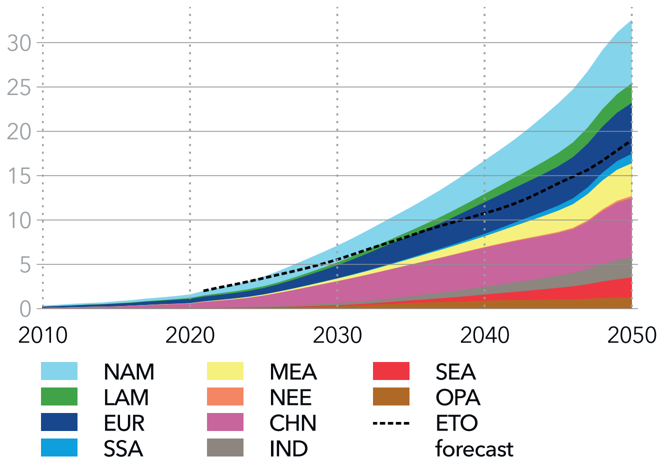


FIGURE 2.10

World wind generation by region

Units: PWh/yr



Historical data source: IEA WEB (2020), GlobalData (2021) system will consist of 7.9 TW of onshore wind, 2.4 TW of fixed offshore wind and 400 GW of floating offshore wind.

The Greater China region (CHN) has the largest amount of electricity generated by wind power in the world at present, and this changes with North America (NAM) overtaking by 2050 in our PNZ (Figure 2.10). CHN and Europe (EUR) are second and third, respectively. These regions are leaders in wind power and the installations of capacities trigger steeper cost reductions for wind power, which bring down costs of these technologies for other regions. This results in significant wind generation in our PNZ even in regions which have historically not invested in wind power, such as South East Asia (SEA). All regions except North East Eurasia (NEE) will have considerable wind-powered electricity in our PNZ.

A considerable number of new wind power plants will need to be installed every year (Figure 2.11) to generate these levels of wind power. From 2020 to 2030, on average, 180 GW of wind power plants become operational every year. From 2030 to 2040, this value increases to 290 GW of wind power plants becoming operational every year, followed by 590 GW per year of wind power plants becoming operational from 2040 to 2050.

As illustrated in Figure 2.11, from 2020 to 2030 for every GW of fixed offshore wind power, 8 GW of onshore wind power plants are built. However, competition for suitable land will increasingly impact onshore wind costs, and at the same time offshore wind costs will decline rapidly. Thus, regions such as NAM and CHN will start investing more in fixed offshore wind power plants. From 2035 onwards, for every GW of fixed offshore wind power plant, only 2 GW of onshore wind power plants are built worldwide. In total, approximately 10% of new power installations are offshore wind power plants, across the world, from 2040 onwards. Such a massive development in fixed offshore wind translates to higher investments in new electricity grid lines, not least undersea cables.

In addition to the grid-connected wind capacity described above, about 1.2 TW of both onshore and fixed offshore wind capacity will be built in our PNZ for dedicated hydrogen production as off-grid capacity by 2050. The majority of this fixed offshore wind will be built in CHN, while most of this onshore wind will be installed in NAM, and EUR.

Other renewable energy and nuclear

The use of renewable energy such as bioenergy and hydropower and nuclear energy changes over time in the PNZ. As mentioned previously, the importance of bioenergy increases greatly in our PNZ, given that there

FIGURE 2.11

World wind gross capacity additions

Units: TW/yr

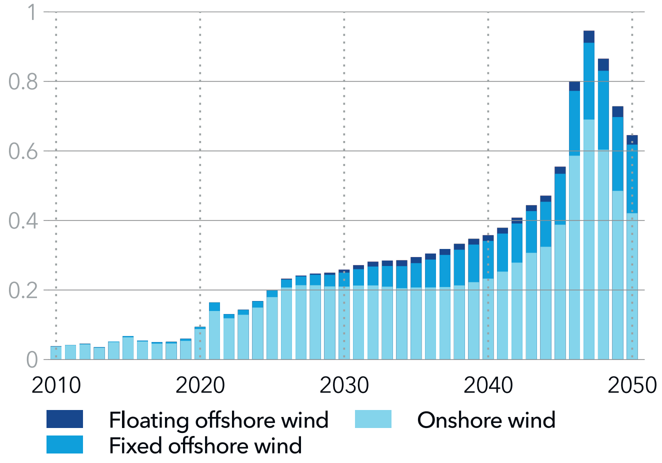
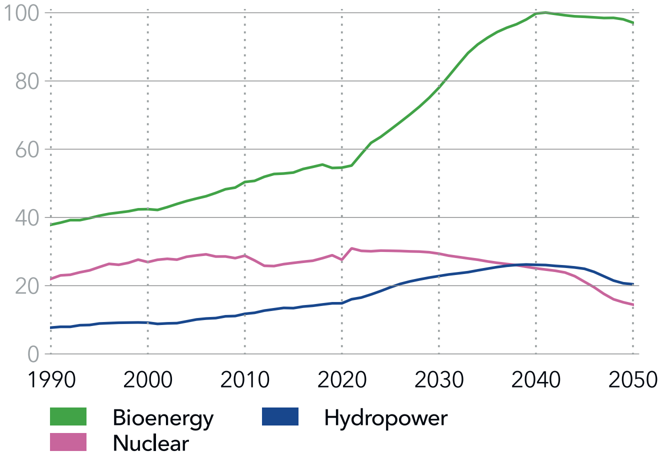


FIGURE 2.12

World bioenergy, nuclear and hydropower supply

Units: EJ/yr

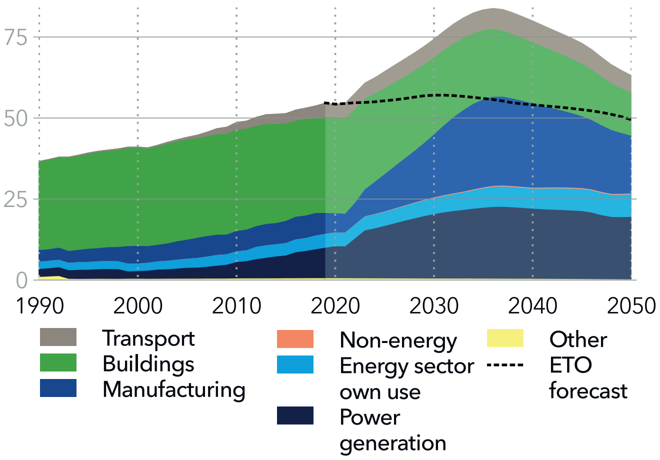


Historical data source: World Bank (2020), IEA WEB (2020) are no easy alternatives for thermal plants which are crucial for regions such as North East Eurasia (NEE). The amount of bioenergy in primary energy supply increases from 55 EJ in 2019 to 97 EJ by 2050 (Figure 2.12). While in our PNZ, the share of bioenergy is 19% in 2050, in our ETO bioenergy had a share of 12%, clearly indicating the criticality of bioenergy in reaching net zero. In contrast, the amount of hydropower increases slightly from 2019 to 2050, but more or less has the same share as in the ETO in 2050.

FIGURE 2.13

Global bioenergy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2020), US DOE (2010), Heat Roadmap Europe (2015)

Unlike many other 1.5°C scenarios, with our PNZ we find that, the role of nuclear diminishes in both absolute energy terms and as a share of primary energy, from 2019 to 2050. The share reduces from 5% in 2019 to less than 3% by 2050. The costs associated with waste disposal, coupled with the drastic cost decreases for solar and wind cause nuclear to play a smaller role in the energy system compared with ETO.

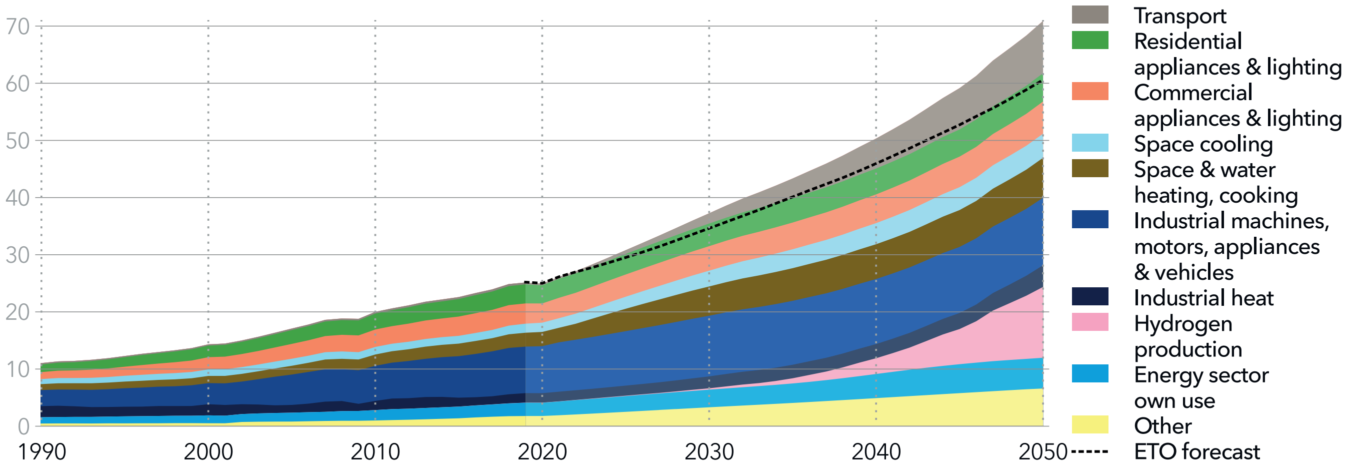
The bioenergy growth in our PNZ undergoes a sectoral demand shift between 2019 to 2050 (Figure 2.13). In 2019, buildings had the largest demand for bioenergy (54%), but thanks to electrification and hydrogen use in buildings, the buildings' share drops to 21% by 2050.

By contrast, we see manufacturing and heat-only power plants using more of the bioenergy in the PNZ, compared with ETO. For example, by 2050, in NAM 57% of bio-energy demand is in the manufacturing sector, and in NEE 91% of bioenergy demand is in heat-only and power plants. In comparison, manufacturing accounted for 16%

FIGURE 2.14

Global electricity demand by sector

Units: PWh/yr



Historical data source: SSB (2021), IEA ETP (2016), Harvey (2014), Nakićenović et al (1996), IEA WEB (2020) of the bioenergy demand, and heat-only power plants 19%, in 2050 in ETO.

The absolute demand for bioenergy in the transport sector grows only modestly from 4.3 EJ in 2019 to 5.5 EJ in 2050. This is in stark contrast to our ETO where the demand grows up to 8 EJ by 2050.

A key takeaway from the PNZ is that we need to change the way bioenergy is currently used to achieve net zero. More bioenergy needs to be used in hard-to-abate sectors like aviation, manufacturing, and heat-only plants, especially coupled with CCS, while bioenergy will be less important in decarbonizing road transport, where electrification is usually a better solution to achieve net zero.

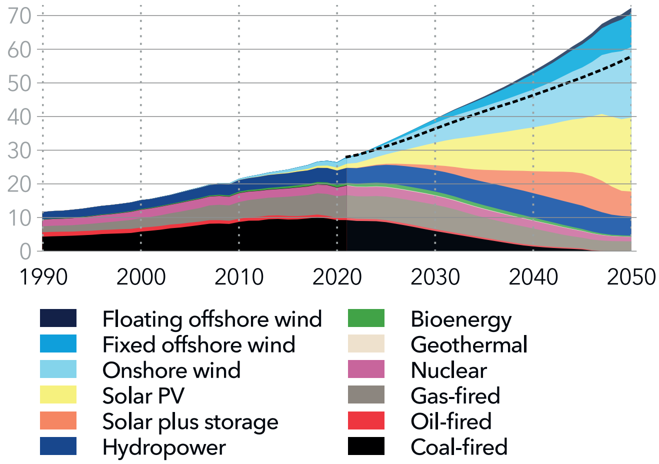
Electricity

In our PNZ electricity demand grows by over 183% from 2019 to 2050, in contrast to the ETO, where electricity demand grew by 116% within the same time frame. All electricity demand sectors are growing in our PNZ (Figure 2.14), which demonstrates the central role electrification will play in decarbonizing the energy system.

FIGURE 2.15

World electricity generation by powerstation type

Units: PWh/yr



Dotted line: ETO forecast. Historical data source: IEA WEB (2020), GlobalData (2021)

The largest increase in demand is seen from hydrogen, where electricity is used to produce green hydrogen from electrolysis. From very low levels in 2019, the power demand for electrolysis, supplied through both grid electricity and dedicated off-grid renewables, grows 400 times its level in 2019 and by 2050, the share of electricity demand for hydrogen is 17%. Since hydrogen is crucial for decarbonizing hard-to-abate sectors, decarbonized electricity is a necessity to facilitate clean hydrogen production. Effectively, this is decarbonization through indirect electrification.

The transport sector sees the next highest growth (28-fold) in terms of electricity demand, where electrification is an important lever for the PNZ in road transport. The share of transport-driven electricity demand grows from 1% in 2019 to 14% by 2050.

While the share of buildings in electricity demand drops from 43% in 2019 to 31% by 2050, in absolute numbers buildings see a near 100% growth due to the rapid expansion of both residential and commercial floor space. This also has positive implications in terms of electricity access and indoor air pollution, especially in developing regions such as Sub-Saharan Africa and the Indian Subcontinent. In these regions, electricity replaces fossil fuels and traditional biomass. The manufacturing sector sees a modest growth of 53% in electricity demand, from 2019 to 2050.

The electricity generation profile of PNZ is radically different from that in 2019, with a rapid near-term phase-out of coal, substituted by solar and wind (Figure 2.15). Solar electricity sees a 39-fold increase from 2019 to 2050, while wind electricity increases 22-fold over the same period. Solar and wind account for 86% of the electricity by 2050. In total, non-fossil sources (renewables and nuclear) account for 96% of the generation, in contrast to ETO, where non-fossil sources account for 84% of the electricity generation by 2050.

Despite the net zero emission constraints, natural gas has staying power in the electricity sector, accounting for 4% of generation in 2050. The North East Eurasia region has the highest share of natural gas-fired electricity generation in the world, where even in 2050, 65% of its generation will come from natural gas. Globally, under our PNZ, all natural gas used in the power sector is abated with CCS. Nonetheless, the negative emissions from biomass-fired power generation are not sufficient in the PNZ to make the global power sector achieve net zero in 2050 (detailed in Section 3.8).

The off-grid solar capacity in the world is 117 GW by 2050, chiefly installed in Sub-Saharan Africa (SSA) and the Indian Subcontinent (IND). Off-grid dedicated renewable capacity for hydrogen production grows from just 4 GW in 2019 to approximately 3.8 TW by 2050. This dedicated renewable capacity will be split equally among offshore and onshore wind, and solar electricity. In contrast, the ETO had only about 1.8 TW of off-grid dedicated renewables for hydrogen production in 2050.

Hydrogen

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. In our PNZ, hydrogen and its derivatives like e-methanol, e-ammonia or sustainable aviation fuels are summarized under the umbrella term of 'hydrogen'.

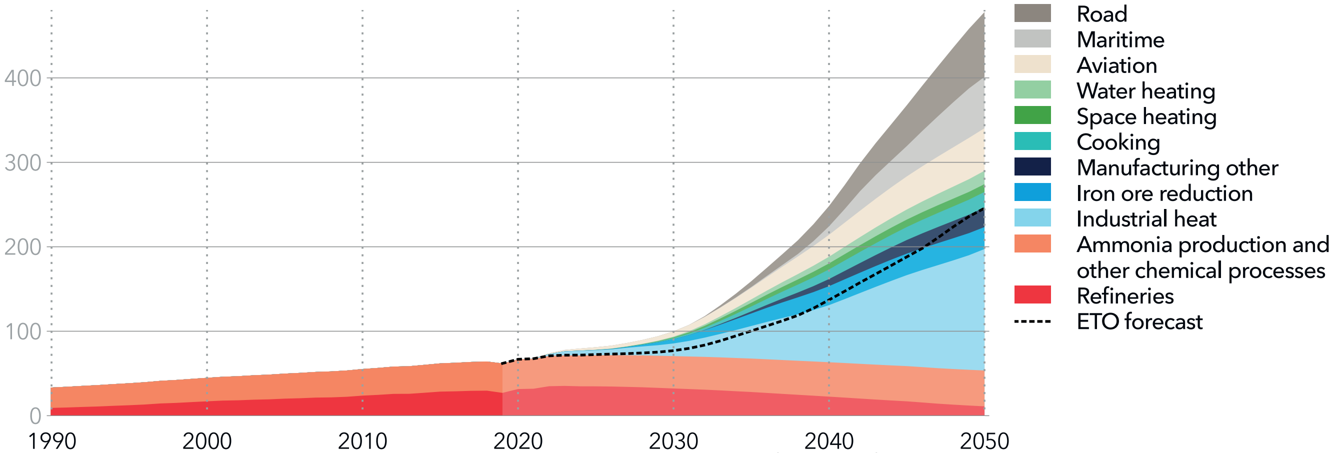
Figure 2.16 shows that one third of global hydrogen and synthetic-fuel demand by 2050 is used for industrial heating. By 2050, 23 EJ/yr of energy demand in manufacturing will be supplied by hydrogen, which represents an 18% share of energy carriers used in manufacturing. Greater China (CHN), North America (NAM) and Europe (EUR) are clearly leading this development with one fourth of hydrogen use in manufacturing in CHN, one fifth in NAM and one sixth in the EUR region.

Road transportation will account for 18% of global hydrogen demand, almost exclusively through long-haul heavy road transport. By 2050, hydrogen will account for 16% of road transport's 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 transportation, which will account for 15% of global hydrogen demand by mid-century. The absence of a significant battery-electric option for most parts of maritime transport leaves synthetic fuels, biofuels, ammonia, and hydrogen as viable options for decarbonization leading to hydrogen and its derivatives supplying 75% of the maritime fuel mix by 2050 in our PNZ. Global aviation will also see a significant share of hydrogen and its derivatives in its fuel mix. 12% of global hydrogen demand comes from global

FIGURE 2.16

World hydrogen demand by sector

Units: Mt/yr



Only includes pure hydrogen demand. Maritime and aviation demand includes synthetic fuels derived from hydrogen.
Historical data source: IEA Future of Hydrogen (2019)

aviation and within aviation, hydrogen will cover about 40% of global aviation energy demand. As with maritime, a lack of battery-electric alternatives makes it more difficult to decarbonize aviation which leads to a higher share of hydrogen in any conceivable net zero pathway.

Only 8% of global hydrogen demand will go to the buildings sector. Strong electrification of buildings end uses such as space heating, water heating and space cooling lowers the need for other fuels for decarbonization. Hydrogen will make only modest progress in replacing natural gas in space heating, water heating and cooking amounting to slightly less than 5% of the buildings sector fuel mix.

Figure 2.17 shows the breakdown of global hydrogen production by source, both for energy and non-energy purposes. The share of non-carbon free hydrogen will be very low by 2050 with less than 5%. Hydrogen from carbon-free sources is shown as two categories: hydrogen supplied via electrolysis from grid electricity; and off-grid dedicated renewable-based electrolysis. In addition, hydrogen can also be supplied from natural gas with associated carbon capture and storage (CCS). By mid-century, the highest share of hydrogen production will come from dedicated off-grid capacities (46%), led by offshore wind, whilst grid-based electrolysis will be responsible for 34% of the hydrogen production by then. 15% will be supplied from natural gas with CCS.

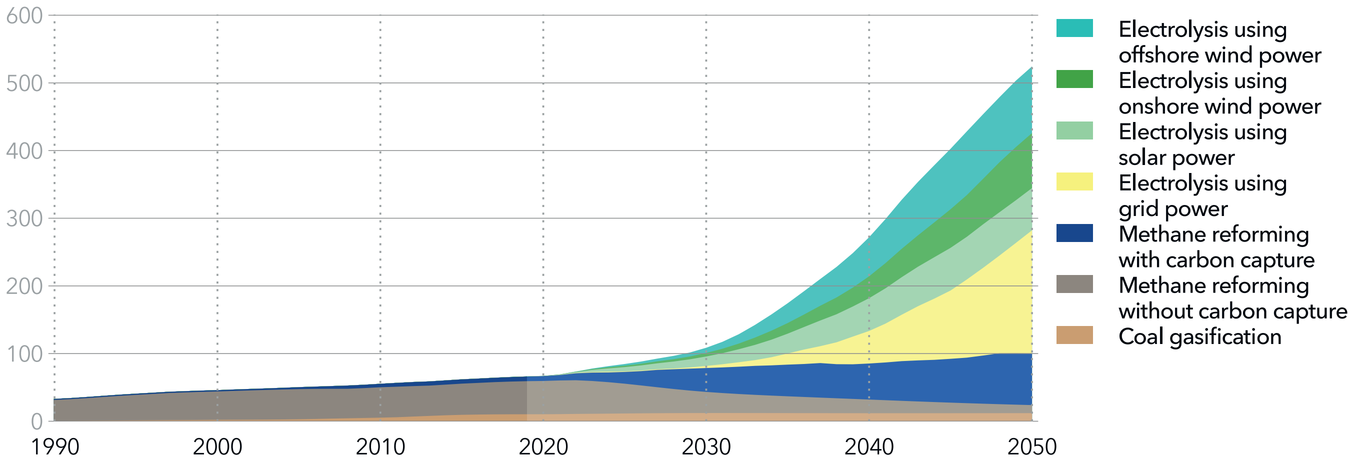
Global hydrogen production needs to significantly scale, and almost double every coming decade to supply our PNZ demand of hydrogen. With this comes a huge capacity build-up. Electrolysis capacity for dedicated off-grid hydrogen production will need to be 0.4 TW in 2030, 1.9 TW in 2040, and 3.8 TW by 2050, clearly led by Greater China and Europe. Grid-based electrolysis will need to follow this capacity ramp-up with about 80 GW of electrolysis capacity by 2030, 530 GW by 2040 and almost 2 TW by 2050. Here, the development is led by North America and Europe. In sum, by 2050, our PNZ will need about 5.8 TW of electrolysis capacity to supply decarbonization in the different demand sectors.

Total hydrogen production in 2050 at 525 Mt/year under our PNZ compares with 280 Mt/year forecast by our ETO. This implies that hydrogen satisfies 13% of energy demand in 2050 in our PNZ versus 5% in our ETO forecast.

FIGURE 2.17

World hydrogen production by source

Units: Mt/yr



Only includes pure hydrogen supply. Historical data source: IEA Future of Hydrogen (2019)

2.3 COSTS AND ENERGY EXPENDITURES

The PNZ is affordable in the sense that it has lower costs than the present energy system. While global GDP will more than double by 2050, global energy expenditures will not grow as fast owing to improvements in energy efficiency and to increasing electrification, which in turn cause final energy demand to fall – a 12% decline compared with 2019 (Figure 2.3). 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. Those higher costs may be used as an excuse for inaction.

Diverting the energy expenditure

Many commentators assume that the transition to a net zero future comes with an unassailable mountain of costs. Our PNZ analysis shows that this is not the case either globally or on a regional level. In some sectors, however, the PNZ calls for higher expenditures. In those cases, conventional technologies are cheaper but come with the externality cost of high emissions.

In our PNZ, as with our ETO, 'energy expenditures', as calculated by the model, includes fossil-fuel extraction, transport, and refinement such as liquefaction, regasification, refineries, and conversion to hydrogen and electricity. Similarly, all costs in the power sector, including power grids, are incorporated, including the installation and operation of renewable energy plants.

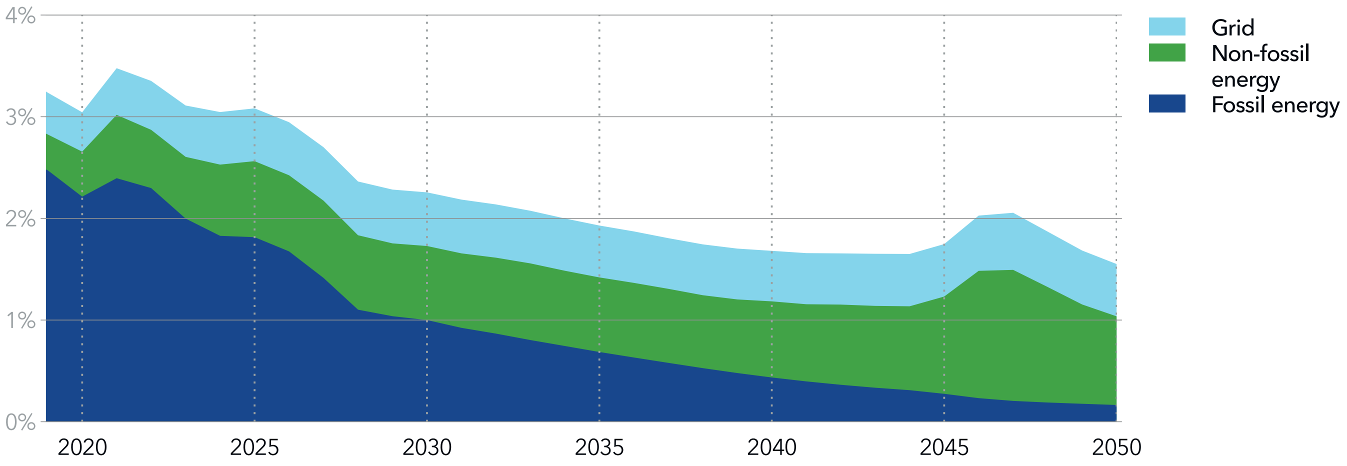
We do not include investments in energy-efficiency measures as well as in downstream carbon mitigation costs. We regard the modelled subsidies that we include in our PNZ as support that benefits consumers and do not count these as energy expenditures. A discussion on their impact on carbon capture is included later. Many of these costs that are not included in the model are still relevant in calculating the overall cost of the PNZ, and we comment on and quantify most of these costs both in this chapter and in the sectoral roadmaps. We provide an assessment of the impact of these additional PNZ costs at the end of this section.

However, with reference to our strict model definition of energy expenditures, we show in Figure 2.18 that despite massive investments in high capital-cost renewables and electricity networks, the share of global GDP allocated to

FIGURE 2.18

World energy expenditures as a fraction of GDP

Units: Percentages



energy expenditures will more than halve, dropping from its current level of 3.2% to 1.4% by mid-century. The main reason for this development is the strong decline in fossil expenditures.

For upstream oil and gas, expenditures will decline by 85% through to 2050. A global ban on new capacity addition by 2028 means that, after that year, expenditures relate solely to the operation of the remaining production fields to supply a rapidly declining market.

The overall picture for power generation is that costs shift from operating expenses (OPEX), dominated by the cost of fossil fuels, to capital expenditures (CAPEX) in renewable power and related installations. Indeed, almost no fossil fuel-fired power investments will be made from 2030, and the remaining costs will be for operating and maintenance until their phase-out in the 2040s.

The progressive decline of fossil fuel-related investment contrasts sharply with higher expenditures in low-carbon power generation, as shown in Figure 2.19. The increase in electricity demand will lead to an almost quadrupling of non-fossil power expenditures by 2050, and total investments of some USD 55trn over the next 30 years. The rise is particularly visible for solar PV and wind power. Together, they will represent a third of global energy expenditures in 2050, an almost eight-fold increase compared with 2019. As discussed more fully in Section 2.2 covering solar PV and wind, the spike in expenditure on power generation from these sources, especially solar PV, from 2045 onwards relates to the rapid phase-out of fossil fuel plants.

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 35trn over the next 30 years. Grid expenditures will almost triple from 2019 to 2050.

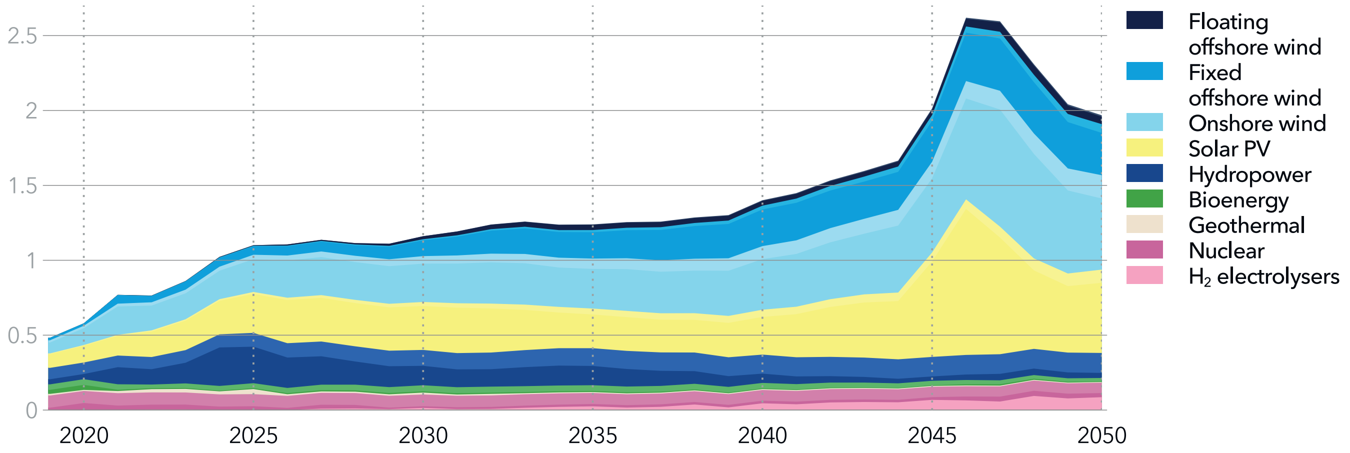
The cost of carbon capture

Not included in the modelled expenditures shown in Figure 2.18 are the costs of carbon capture, use and storage (CCUS) and direct air capture (DAC). These will account for significant spending reaching USD 750bn by 2050, equal to 0.3% of global GDP in 2050. Figure 2.20 shows the world's total expenditure on carbon capture and removal technology needed to realize the transition to net zero emissions.

FIGURE 2.19

World non-fossil power expenditures

Units: Trillion USD/yr



Government support

Financial support from governments is an essential part of the PNZ and decisive for the decarbonization of several sectors.

By multiplying regional carbon emissions by carbon prices, we derive a rough overview of regional carbon-pricing revenue generated by passing the cost of emitting to emitters. This estimate is not entirely accurate, as not all sectors apply the same carbon rates, e.g., the transport sector typically has other forms of fuel taxes, but the estimate gives a reasonably good indication of the levels of carbon-related revenue generated. As can be seen from Figure 2.21, global energy-related carbon-pricing revenue will rise from around USD 500bn/yr today to almost USD 2,000bn in 2030, before falling again to less than USD 500bn /yr in 2050. Greater China has the biggest share by far, followed by North America and Europe; all three regions having relatively high carbon prices.

These carbon revenues are likely to be at least partially refunneled back into the respective energy sectors in the form of decarbonization support to net zero priority areas. Such support is key to ramping-up core abatement technologies.

Figure 2.18 shows energy expenditures under the PNZ in accordance with our strict definition of what constitutes energy expenditure. Those expenditures total 1.4% of GDP in 2050. However, as we have discussed in some detail, there are additional costs associated with our PNZ. The sum of these additional costs amounts to less than 1% of GDP (USD 3trn) in 2050. Total expenditure on the PNZ is therefore something in the region of 2.3% of GDP in 2050 – considerably less than 3.2% of world GDP currently spent on energy.

Hence, we conclude that the PNZ is affordable. It is, however, by no means cheap, and requires large upfront investments, much of which, we hope, will be subvented by funds generated by carbon pricing policies.

> Financial support from governments is an essential part of the PNZ and decisive for the decarbonization of several sectors.

FIGURE 2.20

World total expenditure on carbon capture and removal

Units: Billion USD

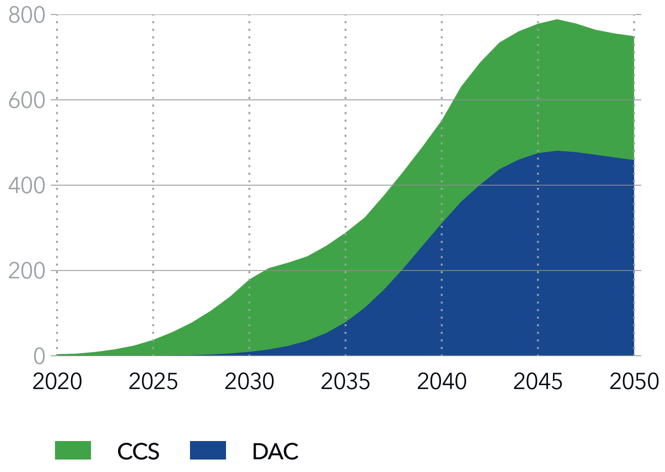
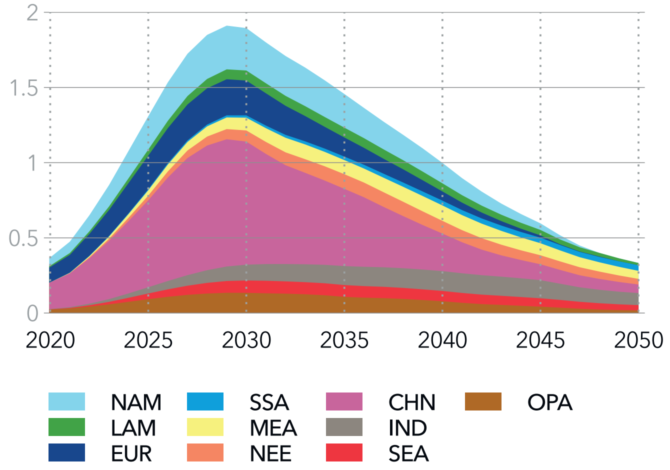


FIGURE 2.21

Indicative carbon price revenue by region

Units: Trillion USD



Solar Panel Farm with unique design in a form of an island (Zoneiland). Energy is used to power city heating (stadswarmte) in a modern sustainable district Noorderplassen in Almere, The Netherlands.

3 SECTOR 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 global energy-related emissions. By mid-century, total emissions from the selected demand and supply sectors are expected to be 2.4 Gt and 0.15 Gt, respectively, under the PNZ, in stark contrast to 8.3 and 2.9 Gt expected in the ETO. The emissions reduction by more than 70% in the demand side sectors and by more than 90% on the supply side (comparing PNZ versus ETO figures in 2050) will be driven by strict and ambitious net zero measures described under each sector.

In terms of sectoral contributions, at present, road transport is by far the largest emitter among the seven demand-side sectors in focus, with a 40% share of the total. By 2050, under the ETO forecast, this sector is expected to remain the sector with the largest share, albeit smaller than today (32%). The iron and steel and buildings heating sectors follow closely behind. Under the PNZ, the road transport sector, with difficult conditions for CCS, still dominates the remaining emissions contributing half of 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 much higher prevalence of CCS in the world's fossil-fuelled plants, as elaborated in the power section (p.48), resulting in power contributing only 0.14 Gt to total remaining emissions. From the negligible 0.07% of demand-side emissions being captured on average today, the average CCS capture rate will be about 12% under PNZ versus only 2.5% under the ETO, with up to 90% of emissions in power generation being captured.

In this chapter we detail the pathways to net zero for the nine chosen sectors on both demand and supply sides covering technologies, policies and investment. 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. Where regions and region abbreviations are mentioned, please refer to Chapter 4 (Regional roadmaps, p.59) for the region overview.

> In terms of sectoral contributions, at present, road transport is by far the largest emitter among the seven demand-side sectors in focus, with 40% share of total.

TABLE 3.1

Emissions, sectoral contributions, and CCS capture rates in 2019

2019			
Demand Sectors	**Absolute Emissions after CCS ($GtCO_2$)**	**Contribution to Total Remaining Emissions (%)**	**CCS Capture Rate (%)**
Road Transport	6.54	40%	0%
Maritime	0.88	5%	0%
Aviation	1.06	7%	0%
Buildings Heating	2.26	14%	0%
Iron and Steel	2.62	16%	0%
Cement	1.05	6%	0.4%
Petrochemicals	1.77	11%	0.4%
Total/Weighted Average Demand Sectors	**16.18**	**100%**	**0.07%**
Supply Sectors			
Power	13.10		0.0%
Blue hydrogen	0.00		90.0%

TABLE 3.2

Emissions, sectoral contributions, and CCS capture rates under ETO and PNZ scenarios by 2050

2050						
Demand Sectors	**Absolute Emissions after CCS ($GtCO_2$)**		**Contribution to Total Remaining Emissions (%)**		**CCS Capture Rate (%)**	
	ETO	**PNZ**	**ETO**	**PNZ**	**ETO**	**PNZ**
Road Transport	2.64	1.23	32%	51%	0.0%	0.0%
Maritime	0.29	0.05	4%	2%	0.0%	0.0%
Aviation	0.83	0.34	10%	14%	0.0%	0.0%
Buildings Heating	1.39	0.14	17%	6%	0.0%	0.0%
Iron and Steel	2.00	0.52	24%	21%	1.2%	36.5%
Cement	0.59	0.08	7%	3%	15.9%	73.3%
Petrochemicals	0.54	0.05	7%	2%	15.9%	73.3%
Total/Weighted Average Demand Sectors	**8.29**	**2.41**	**100%**	**100%**	**2.5%**	**11.9%**
Supply Sectors						
Power	2.91	0.14			2.8%	89.7%
Blue hydrogen	0.02	0.01			90.0%	95.0%

3.1 ROAD TRANSPORT

In our PNZ, final energy demand from global road transport is reduced by a quarter in 2050 compared with DNV`s ETO. Oil use falls by 66%, with electricity (+27%) and hydrogen (+475%) filling the gap. From this development, an emission reduction of 54% is achieved. While the number of vehicles is equal between ETO and the PNZ, the composition of the world`s fleet differs significantly, showing increased battery electric vehicle uptake in all categories.

Technologies

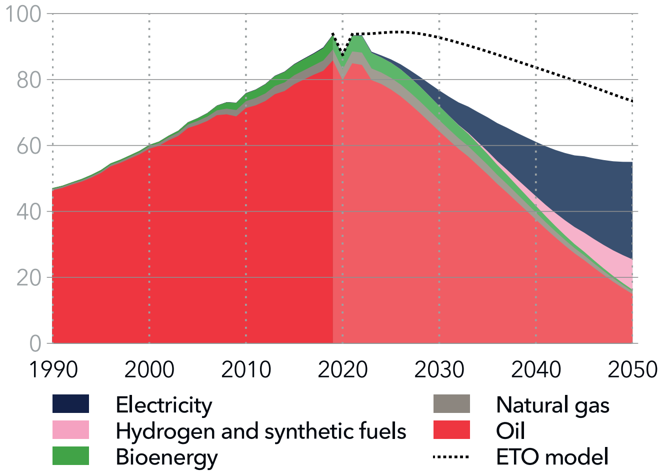
The basic technologies to reduce sectoral emissions in road transport already exist. In passenger transport, the main mechanism to reduce emissions is replacement of ICEVs by EVs. EVs are about three times more efficient than ICEVs, and as the EV fleet expands, energy demand for road transport declines significantly. Moreover, EVs become progressively less emissions-intensive with the ongoing penetration of renewables in the power mix. New models of EVs are already proliferating driving further improvements in vehicle performance measures such as range on a single charge. This applies to both passenger and commercial EVs.

Heavily linked with the uptake of EVs is the availability and average charging speed of recharging stations. New lithium-ion battery configurations as well as new solid-state batteries are likely to increase charging speed significantly, which is highly necessary for operating heavy commercial-vehicles with battery sizes exceeding 400 kWh. At the same time, the availability and average charging speed of public charging stations needs to follow the development of battery charging speed.

FIGURE 3.1

World road transport energy demand by carrier

Units:EJ/yr

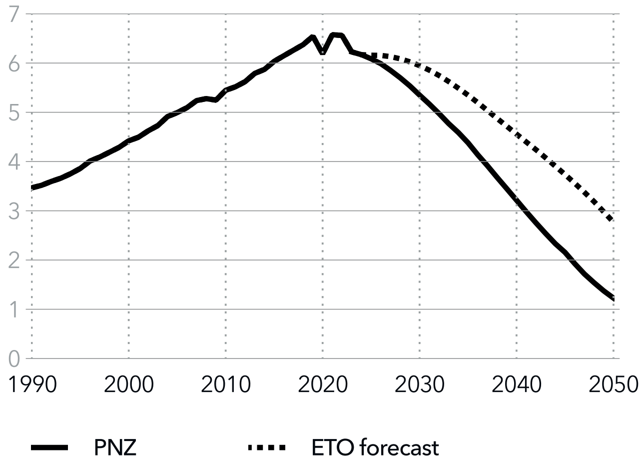


Natural gas includes LPG. Historical data source: IEA WEB (2020)

FIGURE 3.2

World road transport CO_2 emissions

Units:$GtCO_2$/yr



Historical data source: IEA WEB (2020)

In accordance with our ETO, we do not foresee a bright future for hydrogen-propelled passenger vehicles in our PNZ owing to higher costs and lower efficiency. Fuel-cell electric vehicle (FCEV) technology is likely to prevail only in long-haul trucking, whereas the advantages of electric propulsion will edge out both fossil fuel and hydrogen in short- to medium haul trucking.

Our PNZ accommodates some fossil fuel-propelled road transport. However, conditions for ICE manufacturers are likely to be very tough: much tighter fuel economy standards will require very large investments in engine efficiency improvements even as ICE sales and thus revenues are declining.

In line with our ETO findings, we do not foresee the transition in road transport to be significantly constrained globally by the availability of raw materials. Imbalances in demand and supply will be solved through collaboration, trade and innovation.

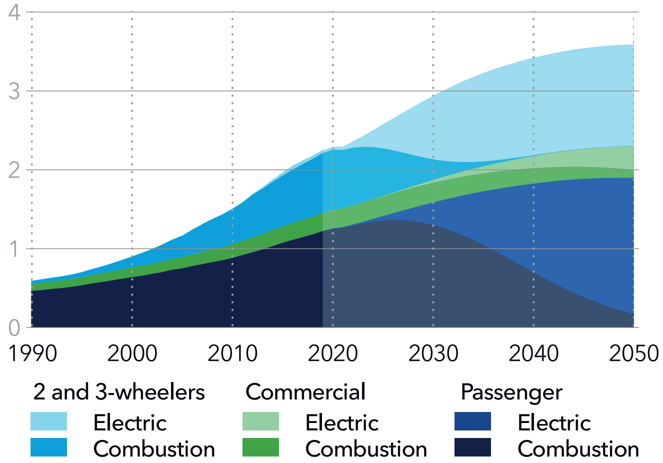
Policies

- Fuel-economy standards will be more stringent. By 2050, there will still be some diesel- and gasoline-fuelled vehicles on the road, but they will almost exclusively be commercial. We believe that those vehicles will have to be subject to much stricter fuel economy standards than currently implemented to reduce their fuel use to a minimum.
- North East Eurasia and Latin America, which have a comparably high share of natural gas-driven vehicles today, are expected to increase the share of internal combustion vehicles propelled by natural gas by 30% in 2050 to contribute to PNZ.
- Additional taxes on gasoline and diesel will be needed to accelerate the uptake of battery-electric vehicles (BEVs), reduce environmental pollution and thus mitigate road transport sector emissions. Taxation levels need to increase by between +75% (Sub-Saharan Africa) and +200% (North East Eurasia and Middle East and North Africa) compared with current levels.
- New sales of internal combustion engine (ICE) vehicles will be banned. OECD regions and Greater China will need to start banning passenger ICE vehicles stepwise from 2030 onwards, with the other regions following only a few years later. However, in Sub-Saharan Africa, it is unlikely that we will see a total ban of ICE vehicles. The prohibition will need to be extended to ICE commercial vehicles, with just a few years' grace period after bans of passenger ICE vehicles.
- The purchase of EVs needs to be further supported by governments and manufacturers with e.g., direct or indirect purchase price reductions heavily weighted to the next few years, and/or quotas for EV shares in manufacturers' fleets.

FIGURE 3.3

World number of road vehicles by type and drivetrain

Units: Billion vehicles



Historical data source: Marklines (2021), IEA EV Outlook (2021), OICA (2016)

Investments

Currently, the purchase of EVs is subsidized in many regions, and this needs to intensify in a net zero scenario. While in some regions a share comes from the manufacturers through discounts, a large proportion is covered by governments. Additionally, further incentives like reduced toll roads or reduced parking fees are in place in many regions. These support measures come with significant fiscal costs. In contrast, fossil-fuel subsidies such as tax breaks on diesel will reduce, relieving governmental budgets.

3.2 MARITIME

Maritime transport needs to reduce its emissions by at least 95% to contribute to a global and cross-sectoral net zero by 2050. Energy demand for global shipping will be about 20% lower compared to DNV's best estimate forecast (ETO).

Technologies

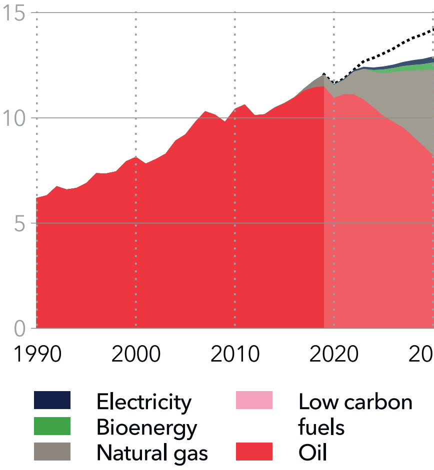
Currently, the world fleet is mostly powered by diesel engines running on marine fuel oils. Decarbonizing shipping will require higher energy efficiency, improved logistics and new fuels. Irrespective of energy efficiency improvements implemented, a change to low carbon fuels will be required to decarbonize shipping by 2050. There has been an increase in the uptake of alternative fuel in ships on order from 6% in May 2019 to nearly 12% in June 2021. Except for the electrification underway in the ferry segment, the alternative fuels are currently still mainly fossil-based – and are dominated by liquefied natural gas (LNG).

All ships will probably not make a transition to the same fuel in the longer term. Our PNZ shows a diverse future energy mix comprising both fossil and low carbon fuels, where fossil fuels are gradually phased out. The fuel mix includes fossil marine fuel oils, LNG and liquefied petroleum gas (LPG), electro-based hydrogen, ammonia and LPG, and bio/electro-based methanol, LNG and marine gasoil (MGO). Key onboard technologies for use of hydrogen and ammonia will be available in 4-8 years, while other technologies are already available. While we expect that the combustion engine will continue to be the dominant energy converter in the fleet, future integration of marine fuel cells in power systems has the potential to provide higher efficiency and thereby lower fuel consumption.

FIGURE 3.4

World maritime energy demand by carrier

Units: EJ/yr



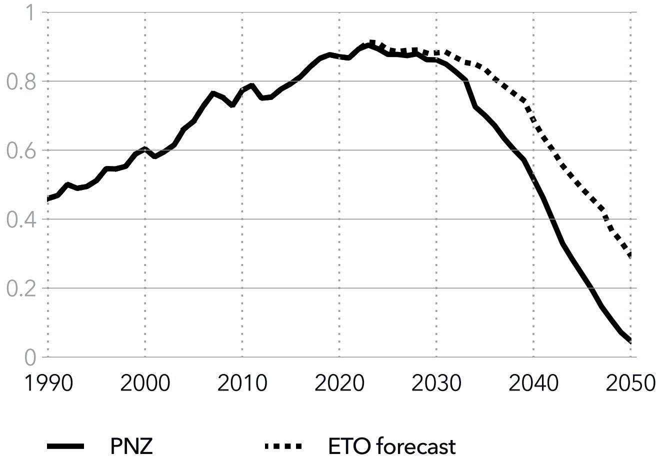
Natural gas includes LNG and LPG. Low carbon fuels include ammonia, hydrogen, eMGO, eLNG, and eLPG.

Dotted line: ETO forecast / Historical data source: IEA WEB (2020)

FIGURE 3.5

World maritime CO_2 emissions

Units: $GtCO_2$/yr



Historical data source: IEA WEB (2020)

The technical applicability and commercial viability of alternative fuels will vary greatly for different ship types and trades. Deep-sea vessels have fewer options compared with the short-sea segment. For the latter, the shorter distances and highly variable power demands often make electric or hybrid-electric power and propulsion systems more efficient than traditional mechanical drives. For the deep-sea segment, most of the energy consumption relates to propulsion at steady speed over long distances, which favours energy efficient mechanical, direct- or geared-driven, two-stroke combustion engines. The ships require fuel that is globally available, and the fuel energy-density is important to maximize the space available for the transport of cargo over long distances.

The future fuel and technology shifts must go together with greater energy efficiency of ships, requiring intensified uptake of both technical and operational energy-efficiency measures. Abatement measures such as wind powering, air lubrication systems, and various hull and machinery measures, are now emerging. The drive for decarbonization in global industrial value chains will also drive logistics optimization including measures such as increased fleet utilization and speed reductions – facilitated by digitalization.

Policies

Three fundamental key drivers will push decarbonization in shipping in the coming decade:

- Regulations and policies
- Access to investors and capital
- Cargo owner and consumer expectations

A clear and long-term predictable regulatory framework for emission reductions will be the key driver for technology development and investments in deployment of carbon-neutral fuels and solutions.

Initial policies need to focus on lowering critical barriers. These include technical maturity and feasibility of technology onboard vessels, including safety and rules, as well as barriers related to market demand. Organization barriers such as managerial practices, legal constraints, and lack of information, will also form substantial obstacles to implementation.

When the main technical and organizational barriers are removed, the solutions need to be implemented in the fleet leading to large-scale uptake of carbon-neutral fuels. This requires large investments, especially in infrastructure related to production and distribution of carbon-neutral fuels and onboard engine and fuel systems.

Enforceable regulations will play an important role in mandating the uptake and creating incentives for investing in production and infrastructure. This could for example be through technical or operational requirements to GHG emissions, or a carbon price ensuring a level playing field for ships that run on more expensive carbon-neutral fuels.

Investments

The total onboard investment costs for the period up to 2050 is estimated in the range of USD 200-450bn, depending on whether the future fuels can be used on existing fuel systems and machinery or not.

In addition to onboard investment needs, the energy transition in shipping will require major investments 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 at least a significant higher fuel cost for ships.

Currently, the world fleet is mostly powered by diesel engines running on marine fuel oils. Decarbonizing shipping will require higher energy efficiency, improved logistics and new fuels.

3.3 AVIATION

The global aviation sector will see a fairly modest growth in our PNZ compared with most other growth forecasts, with the number of flights increasing globally from 4.4bn today to 7.2bn passenger flights per year in 2050. Due to introduction of decarbonized fuel, emissions reduction from the sector is 68% from today to 2050; remaining emissions are at 340Mt CO_2 in 2050.

Technologies

Aviation is a hard-to-abate sector with opportunities for electrification limited to short-haul flights, representing only a small fraction of aviation fuel use. Decarbonization therefore needs to focus on the decarbonization of the fuel itself.

Efficiency, as measured in energy use per passenger-km, will continue to improve due to better engine technology, improved aircraft design, larger planes as well as better flightpath logistics. Annual efficiency improvements will, however, decrease from 1.9%/yr today to 1.2%/yr in 2050.

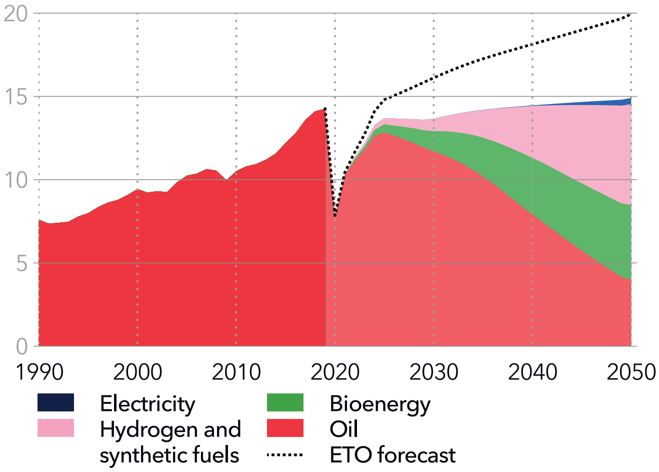
Deployment of electric aircraft is likely to start before 2030 for very small short-haul planes, and in the 2030s for slightly larger short-haul planes in leading regions. Batteries have very low energy density, and only hybrid-electric solutions are relevant for medium- and long-haul. Since only a minor part of aviation fuel is consumed on short-haul flights, electricity will represent only 2% of the aviation fuel mix in 2050.

The aviation industry has started to direct extensive research into hydrogen as a future aviation fuel, with early indications pointing to hydrogen being most promising for medium-haul aircraft. There are technology, cost, and regulatory challenges aplenty, and realistically, we will

FIGURE 3.6

World aviation subsector energy demand by carrier

Units: EJ/yr

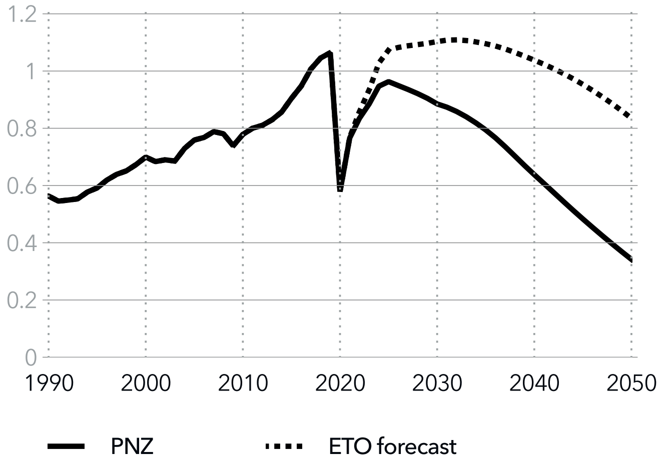


Historical data source: IEA WEB (2020)

FIGURE 3.7

World aviation CO_2 emissions

Units: $GtCO_2$/yr



Historical data source: IEA WEB (2020)

see hydrogen-powered airplanes in use only after 2040 in the first few regions, with limited wider uptake before mid-century.

Sustainable aviation fuel (SAF) can replace the existing kerosene with relatively little adjustment of fuel tanks and engines (depending on blending ratio). In the short and medium term, SAF is likely to consist mainly of biofuels produced from feedstocks such as used cooking oil, municipal solid waste, grassy crops and algae and through conversion technologies such as hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK), Fischer–Tropsch, pyrolysis and alcohol to jet. In the longer term, other SAF solutions will be developed, and liquid synthetic fuel originating from hydrogen is likely to represent more than half of the SAF in the developed regions. As for most synthetic fuels, the efficiencies in the entire production process are low.

Policies

- Increasing fees and taxes, and more costly fuels, make airfares expensive, and are likely to be effective enough on their own to limit growth in the number of flights. Flying can be perceived as a luxury and restricting the number of flights per person is a possible auxiliary policy.
- Mandates on fuel targets and blend-ins will drive decarbonization of the fuel mix. In the foreseeable future, oil-based aviation fuel will remain cheaper than alternative fuels and technologies, including biomass-derived or electricity-based sustainable aviation fuels, pure hydrogen, or batteries. Consequently, fuel blending mandates will be the main policy tool enforcing uptake of low carbon fuels, and we have applied the following scale-up, depending on region and length of flight.
  - NAM/EUR – gradual scale-up to 15% in 2030, 40% in 2040 and 75% SAF blending in aviation kerosene in 2050
  - OPA/CHN – scale up of levels of SAF about 75% of the level in NAM/EUR
  - LAM/NEE/MEA/SEA/IND – scale-up of levels of SAF about 50% of level in NAM/EUR
  - SSA – scale up of levels of SAF about 25% of level in NAM/EUR
  - Flights between leading and lagging regions will follow the leading region's uptake
- Technology mandates for electric short-haul flights are likely and have been applied up to 80% for short-haul flights by 2050 in leading regions.
- Energy-efficiency improvements, in addition to fuel blending mandates and taxation, are expected to continue, but more as a factor of cost reduction than policy, as elaborated below.

Investments

In our ETO we have already included a quite significant SAF share. This comes with additional costs; and we believe the aviation sector is able to finance this through higher airfares. A further enforcement of fuel blending mandates comes with additional costs. However, more expensive flights, potentially paired with behavioural measures discouraging unnecessary air travel, will reduce the number of flights. The absolute investments for society in aviation is therefore lower rather than higher in this PNZ compared to the ETO.

3.4 BUILDINGS HEATING

The building space and water heating subsector is considered hard-to-abate. In our PNZ, we see an emissions reduction of 94% from 2019 to 2050 in building sector heating, and energy use 44% lower in 2050, compared with our ETO. Such a drastic reduction in energy use and emissions is only possible through the dual catalysation of energy efficiency and electrification to drive decarbonization.

Technologies

The technologies for achieving net zero emissions in building heating already exist. Therefore, it is the rate at which such technologies are taken up in the various world regions that makes all the difference in terms of emissions reduction. Main decarbonization options include:

Electrification of building heating with both conventional electric heaters and heat pumps. Technological leapfrogging to electric heating in regions such as SSA and IND, where electricity replaces conventional biomass use, rather than coal, oil, or natural gas. This is possible due to faster technology transfer to these regions from OECD regions.

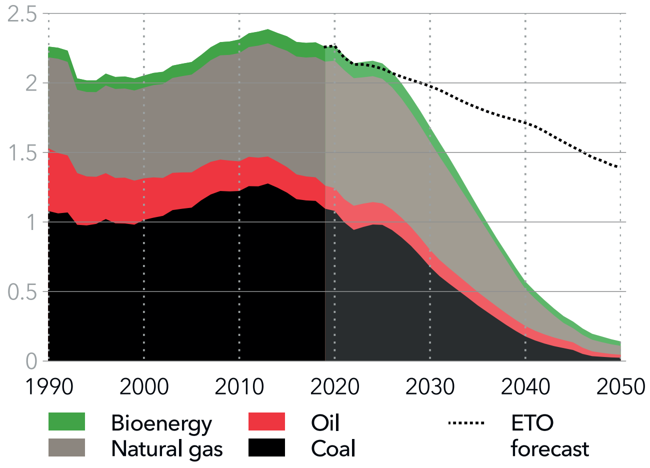
Hydrogen is also used in building heating in the OECD Pacific (OPA) to decarbonize buildings, in tandem with electrification.

Energy efficiency improvements such as innovative building materials and thermal envelopes reduce the specific heating demand. This is not just technology dependent in the sense that the uptake of these options can be encouraged by lower specific heating demand requirements through policy.

FIGURE 3.8

Buildings heating emissions by energy carrier

Units: $GtCO_2/yr$

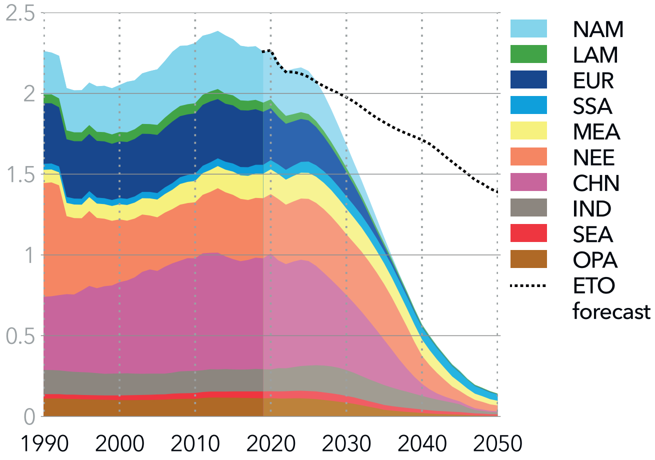


Historical data source: IEA WEB (2020)

FIGURE 3.9

Buildings heating emissions by region

Units: $GtCO_2/yr$



Historical data source: IEA WEB (2020)

Policies

The policy adjustments listed below should not be considered in isolation, but rather in tandem with the available technologies:

Regulation prohibiting fossil-based heating with a partial ban, translating to a limited and regionally differentiated percentage of new buildings allowed to use fossil fuels:

- In NAM, EUR, CHN and OPA, only fossil fuel heating is constrained to 50% of new buildings in 2050, while for the rest of the world 75% may be fossil fuel-heated.
- The lifetime of fossil fuel heating equipment is halved, from 15 years to 7.5 years, enabling faster phase-out of fossil-fuel equipment and hence phase-in of electrification of building heating. Such a halving also has the effect of increasing the levelized cost of heat provided by fossil-fuel equipment. Coupled with leapfrogging (mentioned in the Technologies section), this has the effect of developing regions such as SSA and IND effectively electrifying building heating to a large extent.

Higher cost of capital for fossil-fuel boilers in commercial buildings:

- Investors in commercial building projects will face difficulty in securing funding for fossil fuel connected buildings. Oil and natural gas boilers have a cost of capital of 17%, except in MEA and NEE where it is 11%, while coal boilers have a cost of capital of 20% in 2050. In comparison, cost of capital of electric and renewable equipment will decrease from 7% in 2022 to 6% in 2025 and thereon.

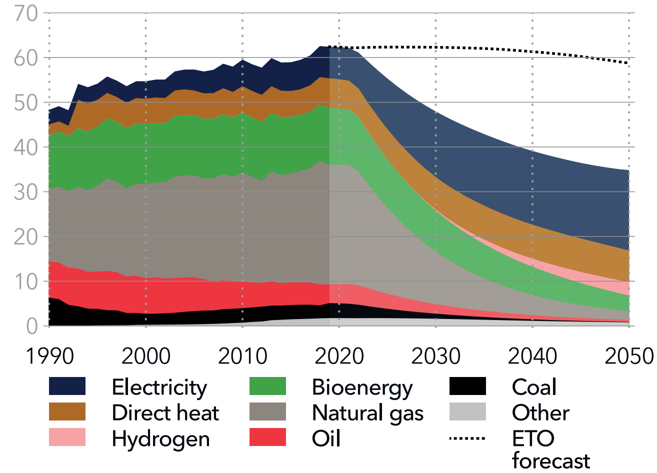
Higher energy efficiency standards for existing and new buildings leading to lower specific heating demand:

- The specific space heating demand of buildings in NAM, EUR and OPA reduces by 2% per year on average from 2022, while in CHN the reduction is 1.5% per year. The rest of the world sees a reduction of 1% per year on average. Additionally, fossil-fuel subsidies for building heating in MEA and OPA are removed from 2022.

FIGURE 3.10

Buildings heating final energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2020)

Investments

The transition we foresee to achieve the PNZ in the building heating sector requires enormous private and public investments into the manufacturing value chain of heating equipment. Joint ventures between private entities from OECD regions and public entities in developing regions are needed, especially given the massive expansion of new building space expected in the coming decades due to the re-structuring toward a more service-based (tertiary) economy. Indirectly, electrification of building heating will also lead to investments into strengthening the electric grid infrastructure, also in countries that currently do not have reliable connection to the electricity grid.

3.5 MANUFACTURING – IRON & STEEL

In our PNZ, global steel production is expected to start declining within this decade thanks to material efficiency and recycling measures. By 2050, the vast majority of steel will be produced in electric arc furnaces. As a result of these and other measures, we foresee an emissions reduction of 80% and an energy consumption reduction of 8% from 2019 to 2050 in iron and steel production.

Due to the high usage of coal, the CO_2 intensity of iron and steel production is significant, with each tonne of crude steel produced resulting in 1.4 tCO_2 of direct emissions, or 2.0 tCO_2 if indirect electricity and heat emissions are included. Iron and steel account for 22% of emissions from manufacturing energy use.

Around 40% of energy demand in iron and steelmaking comes from the reduction of iron ore, a process currently relying predominantly on coal used in blast furnaces. The high share of coal in the sector's energy inputs, the long lifetime of incumbent assets, as well as typically low margins in a mature, competitive and commoditized market pose major barriers to lowering emissions. Furthermore, many technologies that are essential in a net zero pathway, such as rail infrastructure, wind turbines and CCS equipment, require large amounts of steel.

As a result of material efficiency and recycling measures, steel demand and production are expected to start to gradually decrease within this decade in our PNZ.

FIGURE 3.11

World steel production by technology

Units: Mt/yr

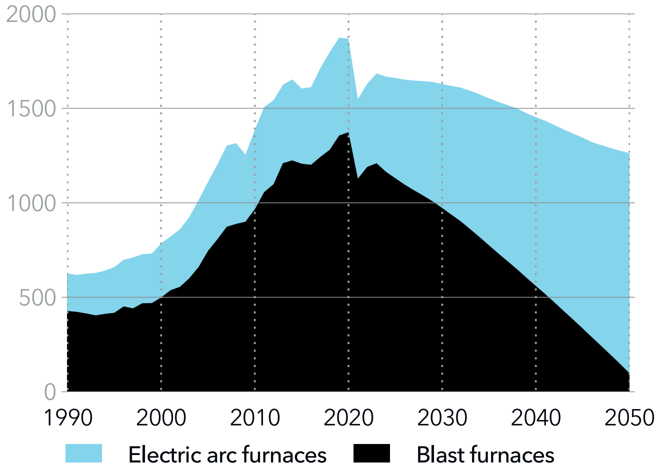
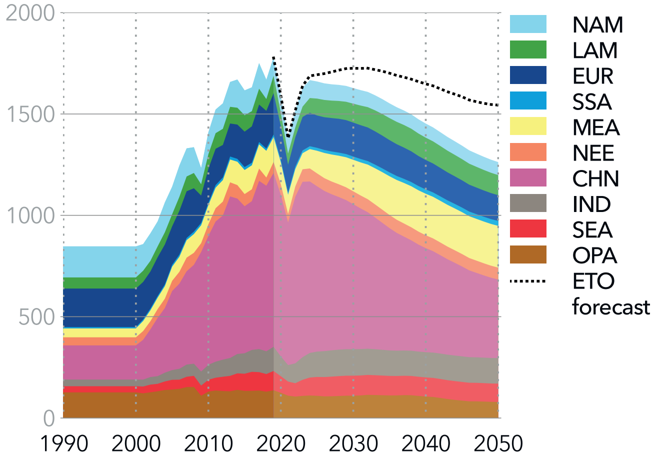


FIGURE 3.12

Steel demand by region

Units: Mt/yr



Technologies

The technologies required for decarbonizing iron and steel production are already available. These mainly include the already widely used scrap-based electric arc furnace (EAF) for steel production, and the promising direct reduction. Direct reduction of iron is the solid-state reduction of iron oxide into iron, where pre-heated iron ore is converted into direct reduced iron (DRI) with hydrogen acting as the reducing agent and energy source. The DRI can then be fed directly into an electric arc furnace to produce steel.

Low-carbon direct reduction can be either hydrogen-based or natural gas-based with carbon capture and storage (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 agent. Therefore, blending of hydrogen into natural gas is seen as a transition strategy before there is technological readiness for pure hydrogen use.

In summary, the technical solutions needed to decarbonize iron and steel exist, but the main barriers are economic (competing with existing fossil-based basic oxygen furnace technology) and policy-related.

Policies

- Carbon pricing is the most important policy for the commercialisation and scaling up of low-carbon iron and steel production. Sufficiently high pricing of carbon emissions, internalizing the cost of negative externalities, is needed for low-carbon technologies to make sense commercially.
- Recycling policy enables a faster transition to steel production via EAF. In our PNZ, by 2050, all steel production in the OECD and 90% of production in other regions is assumed to be via EAF (Figure 3.11), and the steel recycling rate climbs to 95% globally.
- Incentives for fuel shifts and CCS. The DRI-EAF technology relies on natural gas or hydrogen for direct reduction of iron, and fuel switching to hydrogen will benefit from lower hydrogen prices (5%-25%) as a result of energy taxation, as well as the significantly faster expansion of global hydrogen production capacity with higher hydrogen uptake in other demand sectors. Furthermore, successful decarbonization of natural gas-based DRI will be dependent on support for the scaling up of CCS technologies (see the Section 3.10 on CCS).
- Substantial regionalized capital expenditure support of between 35% to 50% is foreseen for hydrogen and electricity use in iron ore reduction, aimed at minimizing the use of coal.
- Further PNZ assumptions towards reducing emissions include a gradual decrease in the steel intensity of new buildings (20% lower by 2050) and a faster improvement of energy intensity in steel production itself (1.2%/yr versus 1%/yr in ETO). The decarbonization routes outlined above are consistent with those outlined by the Energy Transition Commission (ETC, 2020) and the International Energy Agency (IEA, 2020).

Investments

The added value of the global steel industry is around USD 500bn (World Steel, 2019). Low-carbon steel production is around 10-50% more expensive than the fossil-based counterparts, with uncertain future CAPEX and OPEX costs and with future energy costs highly sensitive to the cost of natural gas and electricity (IEA, 2020). Assuming the cost difference of innovative technologies would be at the lower end (10%) by 2050, this would translate to an additional annual cost of around USD 35bn for the global steel industry.

Currently, sustainability certification initiatives, such as Responsible Steel, and industry associations that make public commitments to procure 100% net zero steel by 2050 are paving the way towards steel decarbonization in pioneering countries. In the PNZ, we envision investments in infrastructure for sustainable steel and for EAF capacities to ramp up faster beyond the OECD regions in which they currently exist. Similarly, to achieve high recycling rates, the infrastructure for collection and processing will need to be embedded in developing regions.

3.6 MANUFACTURING – CEMENT

Although controversial, cement's unique properties make it unlikely to be replaced in the coming decades. Massive deployment of CCS and a new material composition will however decrease the CO_2 emissions from 2.7 Gt today to 0.1 Gt in 2050.

Technologies

Reaching 4.1 billion tonnes in 2019, cement production accounted for around 7% of global CO_2 emissions. While maintaining production at today's levels, emission intensity will need to decrease by 48% by 2030 and 95% by 2050 in our PNZ. Clinker, the main component of cement, is the most energy-intensive and carbon emitting component of cement production, for two reasons:

- Combustion-related emissions from energy use (1.1 $GtCO_2$ in 2019), where the high heat process around 1500°C in clinker production predominantly relies on high carbon emitting fossil fuels such as coal and pet coke and have limited electrification potential.
- Process-related emissions (1.6 $GtCO_2$ in 2019), where the use of carbonated minerals (mostly limestone) as a raw material releases CO_2 as part of the production process.

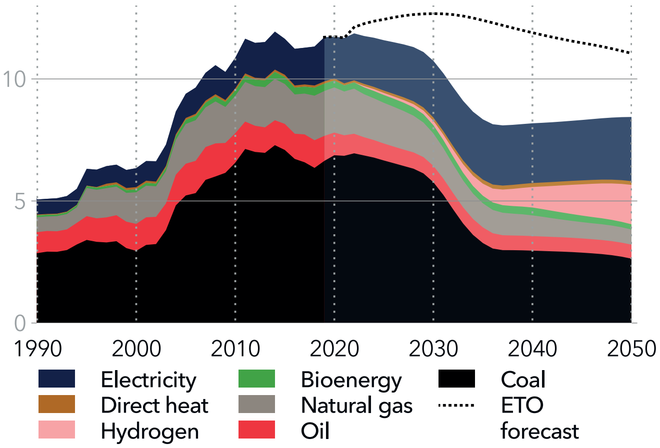
Our PNZ sees three main decarbonization routes:

Carbon capture and storage (CCS) is the main and most effective abatement solution, because of unavoidable process emissions, and will capture 50% of direct emissions by 2031 and 87% by 2050. Technology is however still in an early phase of deployment, with only a handful of projects being announced for the moment. A serious ramp-up will be necessary to unleash the snowball effect of technology cost learning to achieve its full potential.

FIGURE 3.13

Cement sector final energy demand by carrier

Units: EJ/yr

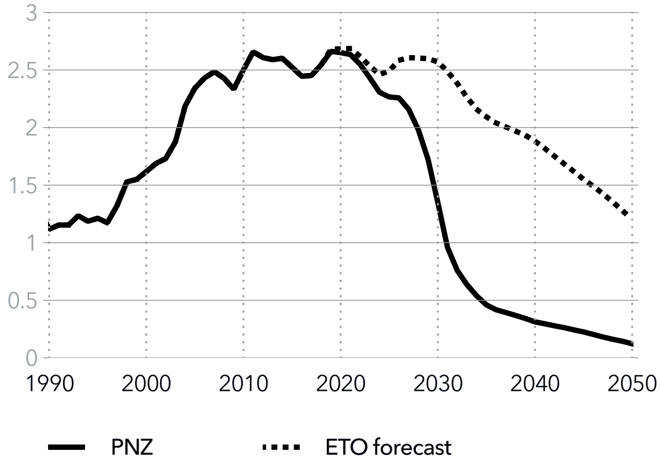


Historical data source: IEA WEB (2020)

FIGURE 3.14

World cement sector CO_2 emissions

Units: $GtCO_2$/yr



Includes process emissions. Historical data source: IEA WEB (2020)

Fuel switching is challenging given compatibility limitations with the dry kiln. Coal use will nevertheless decrease by 63% because of increasing energy prices, the last users being in the Indian Subcontinent and South East Asia. Hydrogen will have an important role and represents 25%, mostly mixed in natural gas. Waste co-processing (plastics, tyres…) will also continue to grow, as it diverts waste from landfill or incineration, and is a source of income for the industry.

Improvements in energy intensity of cement will be made through lowering the clinker-to-cement ratio and the use of alternative materials for clinker or cement, which simultaneously impact process emissions intensity, reducing by 30% in 2050. Minor gains are expected from reuse of concrete because, unlike other raw materials, there is currently no viable technology to perform cradle-to-cradle recycling for cement. Although a lot has already been achieved by phasing-out older technologies, such as wet kilns, further 25% gain in energy-efficiency is expected.

Current cement installations are quite young, especially in developing regions, and have a long lifespan: most of 2050 production will be performed in plants that already exist, and where retrofitting will be the favourable abatement option.

A future potential abatement solution is the impact of recarbonation. This is a natural process, in which finely ground concrete partly reabsorbs the atmospheric CO_2 released during the production, which could significantly reduce the overall process emissions, but the potential requires further study and has not been assessed in the PNZ.

Policies

Decarbonization of cement with high reliance on CCS will not be cost-competitive without policy measures nudging emissions reduction and implementation of solutions.

- Carbon pricing is the strongest policy mechanisms in our PNZ. The effect is observable already today in the EUR region, with sufficiently high carbon prices to increase the share of alternative fuels. To prevent traditionally local cement production from moving to low-cost regions, we expect that carbon price disparities will be handled through implementation of carbon-border adjustment mechanisms that reduce the risk of carbon leakage. This is specifically relevant for cement, being a low value-added product generating 6.9 kg CO_2/USD revenue, far above steel 1.4 kg CO_2/USD (McKinsey, 2020).
- Increased taxation on fossil fuels will trigger fuel switching away from coal and boost the use of less energy intensive cement.
- Regulation and government promotion supportive of new and alternative materials, enforcement of public procurement for low-carbon cement, and eased regulation on cement composition for different use. The superior qualities of concrete make the construction sector reluctant to transition away from the current composition of cement, hence the need for active promotion from governments to reduce the carbon footprint of cement.

Two regions, Greater China and the Indian Subcontinent, will be the locus of decarbonization efforts because together these two regions account for more than 60% of cement production over the 2021-2050 period. Emissions in those two regions will decrease by 90% compared to our ETO forecast, while maintaining a similar output. In developing regions, policies will walk the fine line between climate objectives and a need for housing and infrastructure for fast-growing populations, highlighting the urgency with which global climate financing for abatement options needs to be deployed.

Investments

Given the predominantly upfront capital costs of carbon capture, CO_2 abatement for cement holds potentially significant economic impact for a sector in which margins have historically been tight. Moreover, cement plants are usually located near quarries, scattered across the landscape and may require considerable investments for the connection to future CO_2 infrastructure and transport networks. As an example, the Energy Transition Commission estimates that decarbonization of cement would double its unit cost (ETC, 2020), which illustrates the coming revolution in this sector.

3.7 MANUFACTURING — PETROCHEMICALS

The chemical and petrochemical industry, relying on fossil fuels also as feedstock, will remain key drivers of oil and gas demand, but the phasing out of coal together with the deployment of carbon capture with significant industry use (CCUS), will sharply reduce the energy and process CO_2 emissions by 94% in 2050.

Technologies

The chemical industry encompasses many products widely used in our everyday lives: plastics packaging, fertilizers, pharmaceuticals, tyres etc. This diversity implies that a broad range of solutions are needed. However, certain key decarbonization options will reduce the direct and indirect emissions of the sector:

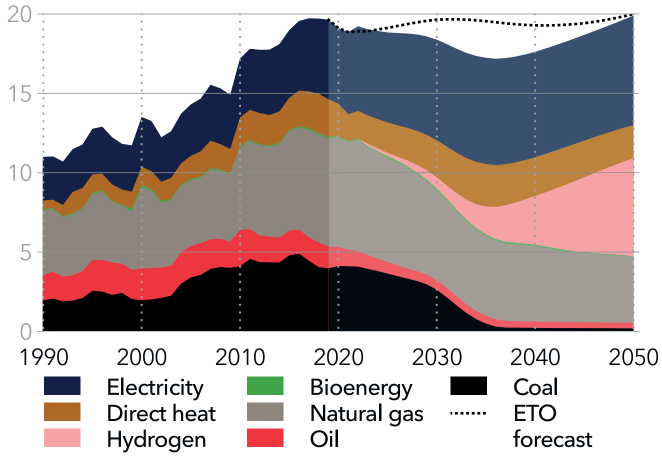
Fuel switching from coal to natural gas for the remaining coal-based methanol and ammonia production, mostly in Greater China. This both increases energy efficiency and reduces emissions intensity. Hydrogen is generated during the reforming process and is an essential part of the reaction. A partial fuel shift to hydrogen from electrolysis is expected. However, carbon dioxide is either recombined directly (methanol) or later (to produce urea from ammonia) in the value chain, so chemical plants must in that case find other sources of carbon, hindering the competitiveness of non-fossil hydrogen pathways and explaining the remaining share of natural gas. These various measures lead to a decrease of process emission intensity by 30% in 2050.

Increased biomethane share, in the methane mix, reaching a global average of 73% in 2050, will induce a net decrease in emissions. Primary building blocks for plastics, or monomers, will continue to be primarily

FIGURE 3.15

Chemicals and petrochemicals final energy demand

Units: EJ/yr

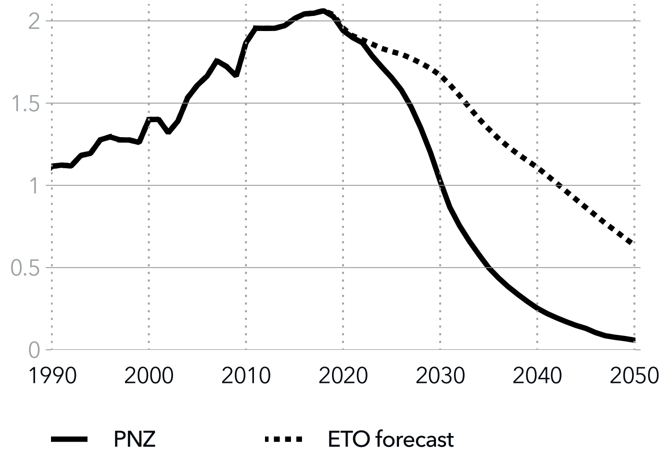


Historical data source: IEA WEB (2020)

FIGURE 3.16

World chemicals and petrochemicals CO_2 emissions

Units: $GtCO_2$/yr



Includes process emissions. Historical data source: IEA WEB (2020) sourced from oil and gas, as processes and current plants are tailored and optimized for these fuels.

Energy efficiency gains of 25% on heat intensity will be achieved through the global uptake of catalytic processes like naphtha catalytic cracking. Gains through electrification will be limited, due to high-temperature processes and to the dual use of fossil fuels as a feedstock and energy source.

Carbon capture, use and storage (CCUS) will abate the remaining emissions. For some processes, such as ammonia production from natural gas, carbon capture has a clear benefit because of the further need for carbon dioxide, 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.

Plastic recycling reaching a 47% average, with regional disparities. Chemical recycling opens new possibilities as described in our *Technology Progress Report* (DNV, 2021). 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. Non-recyclable polymers should be directed towards waste-to-energy (including co-processing) and waste-to-fuel technologies for a better use of the embedded energy.

Policies

Policies in our PNZ will target the chemical and petrochemical sector broadly, both on its direct and indirect emissions.

- Carbon pricing encourages fuel switching and retrofitting with CCUS on existing plants, especially for hydrogen production from natural gas.
- Policy intervention on plastics includes mandated recycling, with a generalization of extended producer responsibility, and taxes on unrecycled plastics, in combination with increasing recycling rates. Indeed, for plastics, around half of carbon is embedded into the material itself, and 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, accompanied by regulations on product design for higher recyclability will also avoid long-term GHG emissions and promotes the use of non-recyclable plastics as alternative fuels source. Reducing the demand, via a ban of substitutable single-use plastics will also have a moderate impact on global emissions.
- Support to decarbonized hydrogen, an essential chemical for ammonia production. Emissions from this key element in nitrogen fertilisers, which currently accounts for around 500 $MtCO_2$/yr, must be addressed while assuring the closely related food security. This will thus remain one of the main concerns for governments.
- Stringent regulation on local nitrate pollution and interventions on food waste reduces ammonia derivatives demand. Although ammonia production is decarbonized, final use of its derivatives and their subsequent soil decomposition are a source of carbon dioxide and nitrous oxide emissions.

> Fuel switching from coal to natural gas for the remaining coal-based methanol and ammonia production, mostly in Greater China. This both increases energy efficiency and reduces emissions intensity.

Investments

Energy efficiency investments on new plants (process, fuel shifts from coal to natural gas) could in fact lead to cost savings (IEA, 2018), although initial capital expenditures could be high.

The most important upfront capital costs will however be the installation or retrofit of carbon capture, or for water electrolysis in the case of hydrogen production. This could lead to cost increase from 15% to 111% for ammonia (Material Economics, 2019) and 50% for ethylene (ETC, 2020).

3.8 POWER

Given that electrification, whether direct or indirect, is central to the decarbonization of all regions and sectors, a renewable and stable power system is critical for achieving net zero. CO_2 emissions from the power sector reduce from 13.1 Gt in 2019 to 0.1 Gt in 2050.

The power sector narrowly misses reaching net zero in our PNZ. The largest regional contributor to power sector emissions is NEE, accounting for 0.6 Gt of the remaining emissions in 2050 (Figure 3.18). Only two regions, NAM and EUR achieve negative emissions in the power sector, and this is achieved by 2036 and 2035, respectively.

Since the power sector becomes coal-free, the largest remaining contributor to power sector emissions is natural gas, accounting for 66% of emissions in 2050 (Figure 3.17). On the opposite side of the scale is biomass-fired power generation, which, when coupled with CCS, provides negative emissions.

Overall, the share of electricity in final energy demand increases from 19% in 2019 to 53% in 2050, which contrasts with our ETO where electricity has a share of 38% in 2050.

Technologies

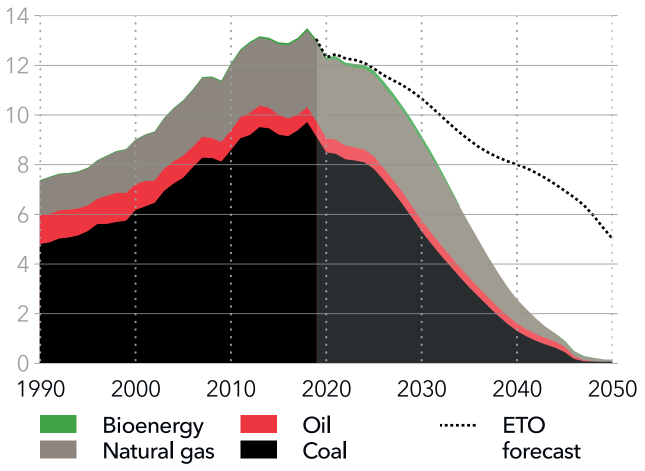
All technologies considered in the power sector of our PNZ exist, and renewable electricity generation technologies are already proven at scale.

Carbon capture and removal – Carbon capture and storage (CCS) is critical to eliminate emissions from the remaining fossil fuel (mostly natural gas) power plants, especially CHP and heat-only power stations that generate heat to district heating systems. There are no renewable alternatives to heat generation except biomass and waste. Therefore, a combination of fossil-to-biomass transition and CCS will be needed to decarbonize heat supply (see Section 3.10 for further information on CCS).

FIGURE 3.17

Power sector emissions by energy carrier

Units: $GtCO_2/yr$

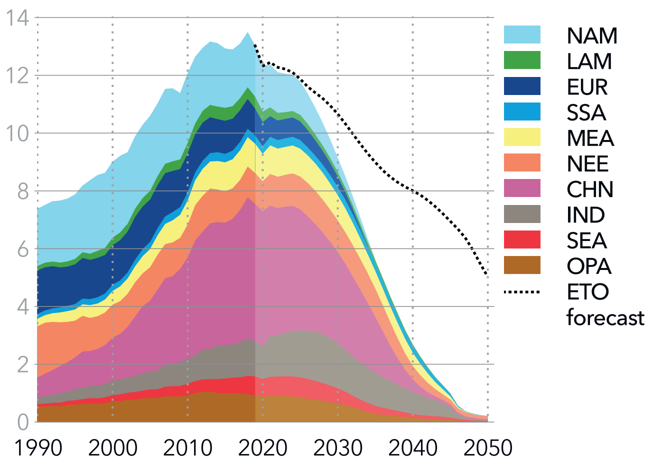


Historical data source: IEA WEB (2020)

FIGURE 3.18

Power sector CO_2 emissions by region

Units: $GtCO_2/yr$



Historical data source: IEA WEB (2020)

Flexibility and digital infrastructure to ensure security of power supply – A very large share of variable renewable energy sources (VRES) in a power system is feared to cause issues of supply stability. A combination of digital grid infrastructure solutions, battery storage and backup dispatchable capacity can help ensure frequency stability, even at 100% VRES penetration. In balancing hourly and daily fluctuations, pumped hydro, battery storage, dispatchable generation, demand response and interconnections will be the key flexibility providers. Low CAPEX natural gas combined-cycle power stations will play a critical role in providing backup capacity to power systems in extreme cases where high demand meets low wind and solar generation. For the continued investment in VRES it is essential that flexibility is built-in and there is sufficient dispatchable power (IRENA, 2019 a,b). Power-to-hydrogen will play a vital role in utilizing excess renewable electricity and avoiding long intervals with zero prices.

Extension of lifetime of nuclear power plants – despite its high cost and waste issues, nuclear power still provides carbon-free electricity and has a role in our PNZ. Although countries such as Turkey and Bulgaria are pivoting to nuclear power at present, we don't expect significant expansion of nuclear capacity due to its cost and long construction times. However, delaying the decommissioning of existing nuclear plants and allowing them to run more flexibly through refurbishments of key components would be sensible, despite the additional cost associated with these refurbishments (IAEA, 2020). Given this, in our PNZ, the lifetime of new nuclear power plants is increased from 75 years to 100 years.

Policies

The policies to achieve a PNZ in the power sector consist of cost of capital for power sector investment, subsidies and other support, mandates, and bans. These policies should be considered in conjunction with the technologies highlighted above.

Cost of capital – In our PNZ, it will be increasingly difficult for project developers to raise equity financing for fossil-fuel power plants, or for that matter to access advantageously priced debt financing. This is reflected as higher cost of capital for investment for fossil fuel power plants, differentiated by fossil fuel type and regions. In contrast, renewable power investments have reduced cost of capital, from 7% in 2022 to 6% in 2025 and thereafter.

- Oil and natural gas power plants have a cost of capital of 11% in Middle East and North Africa and North East Eurasia, while the rest of the world has 17%.
- Coal power plants will have a cost of capital of 20% without any regional differentiation.

Investment support for storage capacity – increased subsidies are given to investment for storage capacities which are coupled to VRES.

Reduced lifetimes of fossil power plants – in our PNZ, new fossil fuel capacity additions from 2022 have reduced lifetimes which are mandated by policy. This affects all three types of fossil fuel power plants, whose lifetimes are reduced from 40 years to 25 years. From 2045 on, residual oil and coal fired power generation capacity is forcibly retired in all regions.

Support and market design to ensure continued investment in renewable power – With high shares of solar and wind in power systems, the electricity prices will become increasingly volatile with extended periods of very low or negative pricing if the electricity markets continue to operate in the same manner as they do today. New market designs or financial support mechanisms to keep capture prices above costs will help to sustain continued power investments.

Investments

The world's power-line grid capacity in PNZ increases by 140% from 2019 to 2050. In comparison, in our ETO the increase was 119% during the same time horizon. World grid costs are approximately 0.4% of the world GDP and this value remains nearly the same from 2019 to 2050. From 13% in 2019, the share of grid expenditures in energy expenditures increases to 33% by 2050. Higher investments into grids will be necessary to support a nearly 100% VRES power system. This will also need to be complemented by the investments into state-of-the-art digital infrastructure to ensure security of power supply.

3.9 HYDROGEN

Hydrogen is now considered the most viable option for decarbonization in many hard-to-abate sectors such as aviation, long-haul trucking, iron and steel production, or high heat processes. Hydrogen from both renewables and from fossil fuels combined with carbon capture and storage (CCS) support a net zero energy system in 2050.

Technologies

The technologies to both supply electrolysers with either renewable power or fossil fuels as well as the conversion to hydrogen via electrolysis or steam methane reforming/gasification are mature and in commercial use. Regarding electrolysers, alkaline electrolysers are more mature than polymer electrolyte membrane (PEM) electrolysers and thus dominate the market at present, but PEM`s advantage in operating more flexibly will increase its share substantially.

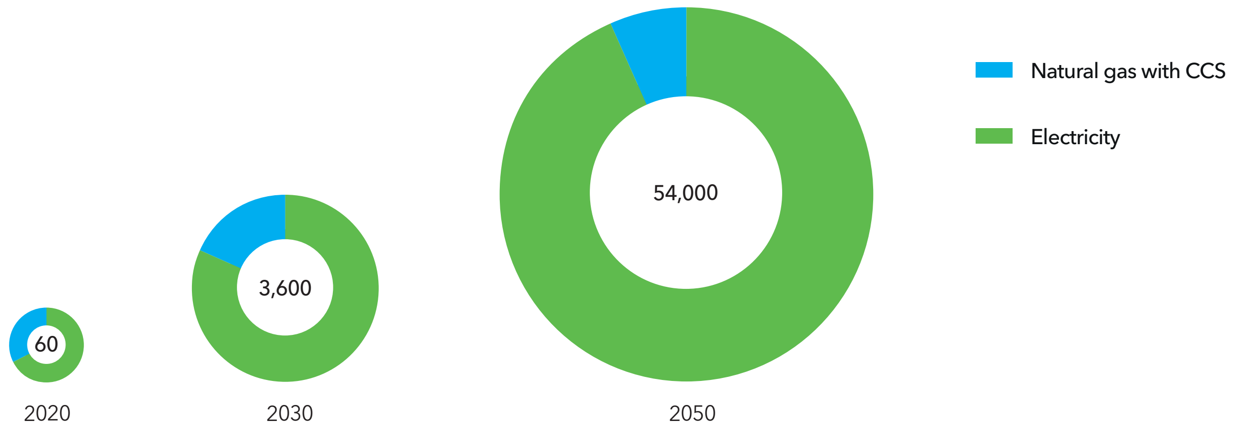
Our PNZ encompasses two main production routes for electrolyser-based hydrogen: grid-based electrolysers and standalone renewables-based electrolysers. To prevent possible future fluctuations of electricity prices, investors will gravitate towards dedicated off-grid renewable generation for hydrogen production. But grid-based hydrogen production will exploit these fluctuations and make use of cheap electricity available for long hours, avoiding curtailment of solar and wind. Alongside electrolysis-based hydrogen production, we will also see a continuation of hydrogen produced from CCS-treated natural gas via steam methane reforming.

With growing installations of renewable power, fossil-fuel based hydrogen for energy purposes will see a large reduction in market share (Figure 3.19).

FIGURE 3.19

Hydrogen production as energy carrier by production type

Units: PJ/yr



Although currently not part of our ETO, we expect that the significantly growing hydrogen production based on burgeoning demand under our PNZ will very likely lead to inter-regional hydrogen trade. We foresee both pipeline and shipping as important means for hydrogen trade, also in combination with hydrogen transformed to larger molecules. Depending on the end use we will see hydrogen blended with natural gas in existing grids (e.g., for buildings gas supply) or dedicated hydrogen pipelines (e.g., in transport).

To conclude, the basic technologies to realise global hydrogen trade exist today. Ongoing R&D effort will need to aim at, inter alia, improving PEM fuel cells and electrolysers as well as storage and transport options through improved tank design and metal hydrides.

Policies

To channel hydrogen use to where its best suited, a PNZ will see sectoral hydrogen support and incentives to create hydrogen demand.

- Energy taxation – Hydrogen consumption in manufacturing will see energy taxation favouring hydrogen to boost e.g., carbon neutral steel or zero emission process heat.
- Mandates on fuel-mix shifts and emission trajectories in aviation and maritime transport will create a significant demand market for hydrogen
- Requirements – Refineries will be required to increase their hydrogen share for energy provision and in doing so advance their own global emission reduction contribution

On the production side, explicit CAPEX reducing measures are needed to boost cost learning curve-based cost reductions for hydrogen.

- CAPEX support to integrated renewable electricity and electrolyser projects, and subsidies to grid-powered, renewables-based electrolysis. Both support mechanisms will be strongest in OECD regions and lower in developing regions.
- Steel production will be backed by support to shift to a hydrogen supply chain.

Investments

Accumulated investment in grid-based electrolysis to provide hydrogen for energy purposes will amount to about USD 1,700bn by 2050 and an additional USD 1,350bn for dedicated hydrogen pipelines. With actions starting soon, this would mean an average global annual investment of about USD 60bn per year for grid-based electrolysis and less than USD 50bn per year for dedicated hydrogen pipelines. Further investments will need to be made for dedicated hydrogen production in combination with renewable power plants as well as for the build-out of the associated infrastructure for integration into hydrogen supply chains.

> To channel hydrogen use to where its best suited, a PNZ will see sectoral hydrogen support and incentives to create hydrogen demand.

3.10 CARBON CAPTURE AND STORAGE

In our PNZ, CCS deployment grows rapidly from around a mere 80 Mt today to nearly 3.3 Gt of CO_2 captured in 2030, reaching a peak of around 5.1 Gt in 2042, before slowly declining back to some 4.7 Gt by mid-century.

Technology-based carbon removal, generally referred to as carbon capture and storage (CCS), is needed to capture emissions that are technically difficult or prohibitively expensive to eliminate. Reaching net zero will be virtually impossible without CCS. Technology per se is not an inhibitor, with CCS facilities having operated for several decades in areas such as enhanced oil recovery or fertiliser production, where the CO_2 can be captured at relatively low cost. However, for as long as there are fossil fuels in the energy mix as well as emissions as part of production processes, CCS will be sorely needed.

The existing 20 or so commercial CCS operations worldwide are nowhere near the level required to move towards net zero emissions (GCCSI, 2021). However, CCS has recently come into focus once again owing to its critical role in hard-to-abate sectors, and its dual role in both reducing emissions and delivering carbon dioxide removal. The contemporary focus on CSS also stems from the realization that a speedy ramp-up of CCS is required immediately – certainly in the remainder of this decade – to unleash technology cost-learning dynamics associated with cumulative increases in installed capacity.

In our PNZ, the amount of carbon captured via CCS starts to become exponential in the second half of this decade, growing rapidly from around only 80 Mt today to nearly 3.3 Gt of CO_2 captured in 2030, reaching a peak of around 5.1 Gt in 2042, before easing to around 4.7 Gt by mid-century in line with a reduced amount of global emissions to capture. In this scenario, the result is that 95% of emissions in hydrogen production, 94% in natural gas production, 90% in the power sector, 80% in refineries, and 95% of industrial process emissions are captured by 2050.

FIGURE 3.20

Emissions capture with CCS by region

Units: $GtCO_2$/yr

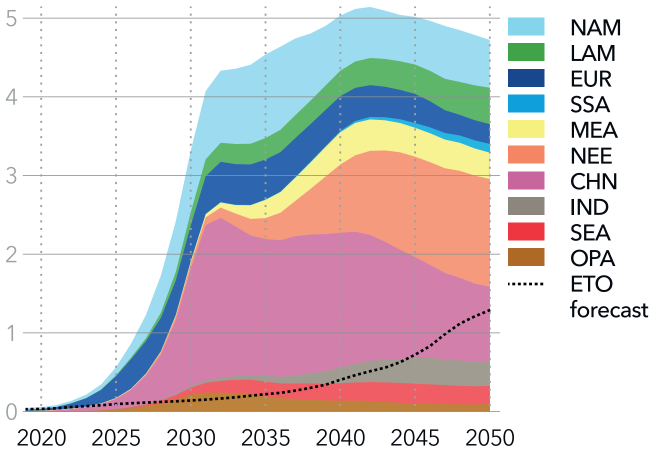
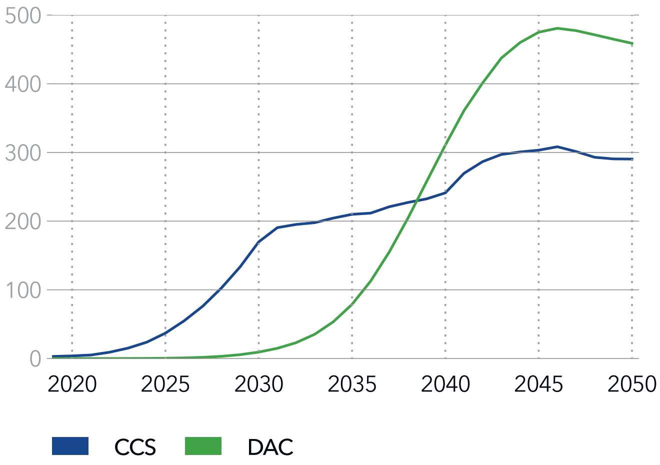


FIGURE 3.21

Global cost of CCS and DAC

Units: Billion USD/yr



Technologies

Infrastructure to transport and store CO_2 safely and reliably is essential for expanding the prevalence of CCS. CCS facilities can either be stand-alone 'point-to-point' projects or 'hub and cluster' networks which bring together multiple CO_2 emitters and/or storage locations using shared transportation infrastructures. Establishing such CCS hubs will help accelerate deployment by reducing costs. At least 12 CCS hubs (GCCSI, 2021) are currently in development globally – including in Australia, Europe, the United States, Canada, and proposals in Malaysia and Indonesia – with many of them linked to low-carbon hydrogen production (IEA 2020). IEA's analysis of CO_2 emissions from power and industrial facilities in China, Europe and the United States finds that 70% of the emissions are within 100 km of potential storage. But shorter distances can reduce costs further and decrease infrastructure development times.

Direct Air Capture

Direct air capture (DAC) technologies have significant potential to accelerate the transition to net zero. DAC technologies extract CO_2 directly from the atmosphere for permanent storage (carbon removal), or for use, for example, in carbonating beverages, in greenhouses, or to produce synthetic hydrocarbon fuels. An advantage of DAC is the potential for flexibility in siting, reducing the need for CO_2 transport. DAC facilities can also be co-located with other CCS facilities, such as CCS-equipped power or industrial plants, to facilitate access to existing CO_2 transport infrastructure and enabling these facilities to reach net zero or even negative emissions. Direct air capture plants are already operating on a small scale, but their costs are currently prohibitively high (IEA 2020). Government support and subsidies can make DAC competitive as a carbon offsetting method over time by progressing the industry's cost learning curves.

When net zero emissions are reached in our PNZ, 3.3 Gt of energy and process CO_2 emissions still remain, notably in the transport and industry sectors. We expect that around 1.1 Gt of these lingering emissions would be captured and stored via DAC technologies. In order to reach this goal, significant government support is assumed in OECD countries and in Greater China, covering respectively 80% and 40% of the gap between unit CO_2 capture cost via DAC and regional carbon prices.

Policies

Cost is the key CCS barrier and the fitting or retrofitting of CCS to power or industrial plants will happen only with government-driven deployment policies. In our analysis, we see regional carbon-price trajectories as the key determinant of the uptake of CCS in power, manufacturing, and industrial processing, in combination with other support measures such as infrastructure and investment support, and incentives per tCO_2, particularly driven by North America, the EU plus Norway and the OECD Pacific region, and from Greater China through mandates. Our PNZ assumes faster ramp-up rates and a higher maximum CO_2 capture rate for CCS compared with the ETO.

In summary, the following are the additional policy assumptions for our PNZ:

- Higher carbon prices incentivizing deployment
- Mandates requiring CCS in natural gas-fired power generation
- CAPEX/OPEX support and policies promoting value chain/infrastructure development enable CCS and direct air capture capacity ramp up

Investments

In line with the growth in CCS, associated capital and operating expenditures are expected to grow to a peak of just above USD 300bn per year by 2046, then declining slowly to just below USD 300bn per year by 2050 thanks to lower emissions. DAC technology is expected to take off around a decade later during the 2030s, with expenditures growing exponentially to reach a peak of USD 480bn per year in 2046. This indicates a unit CO_2 capture cost that is over six times higher in DAC, compared with conventional CCS, by 2050. Because DAC technology is still in its infancy, it will require much higher levels of government support. In order to reach the required level by 2050, we have assumed that initially up to three quarters of the costs are subsidized, with the need for subsidies declining over the years down to around 30% by 2050.

3.11 ENERGY EFFICIENCY

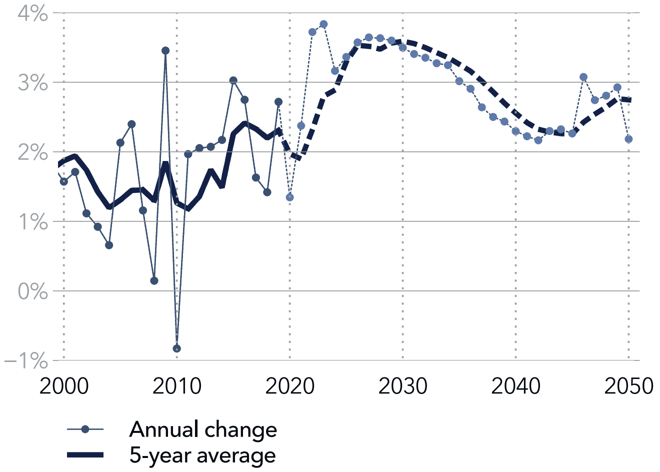
With a great deal more electricity in the energy mix, one would expect our PNZ to generate higher energy efficiencies relative to our ETO. This is indeed the case, with world energy intensity, as measured by primary energy consumed per unit GDP, declining by 2.9%/yr from 2015 to 2030. However, even with this gain, the world still falls short of the 2030 SDG#7 target of doubling the global rate of energy efficiency improvement above the 2000-2015 average of 1.6%.

As things currently stand, the clean alternatives for incumbent fossil technologies in sectors like aviation, maritime, high temperature industrial heating, and iron and steel, are generally too expensive, immature, or even infeasible. However, improving energy efficiency beyond historical trends is not only desired but required for any short- or medium-term emission reduction in these sectors. Even in sectors like residential heating, where electrification is economically competitive, the transition does not happen overnight. So, measures like better building insulation will help reduce emissions of the existing building stock while the installed equipment base is gradually replenished. In most easy-to-electrify sectors, electrification and energy efficiency investments are the easiest way to reduce emissions in terms of technological availability and cost. Most of the high-efficiency technologies are currently available in the market. Moreover, these technologies are either already at cost parity with the incumbent or about to become so soon in terms of total cost of ownership. However, as we see in the examples of EVs, heat pumps or LED lights, the upfront cost of the new technology is usually higher than the conventional alternative. Enacting smart policies to overcome this initial barrier is critical.

FIGURE 3.22

Annual rate of energy intensity improvements

Units: Percentages/yr



Technologies

Previous sections discuss specific technologies that are needed to reach net zero or close to net zero in various sectors. To recap, there are three main paths to improve energy efficiency:

Incremental changes in existing technologies: continued improvements in the efficiencies of various engines and boilers to reduce factors like heat losses and friction. The efficiencies of technologies like internal combustion engines, gas turbines or jet engines have been improving over many decades and many are already reaching their thermodynamics limits. But wherever possible, even small improvements will help reduce emissions. These improvements will make significant differences, especially in hard-to-abate sectors where technology switching is either costly or impractical.

Switch to more efficient technologies: EVs and heat pumps are typical examples where the switch to a more efficient technology can bring a 3-4-fold improvement in energy efficiency. This efficiency leap is the primary driver of electrification, and as the electricity mix becomes greener, electrification investments will translate into further emission reductions.

Measures to reduce energy demand: better insulation of building envelopes or better aerodynamics of transport vehicles help to reduce energy consumption while providing the same amount of (or even superior) energy services.

Policies

Although there is a market incentive for improving the energy efficiency of technologies, reaching net zero requires significant additional policy support for energy efficiency. There are two main reasons for this. Firstly, the rate of energy efficiency improvements needed to reach net zero is typically faster than the historical improvement rates realized by market-driven research and development. Secondly, we will need to continue investing in the energy efficiency of soon-to-be-obsolete technologies like internal combustion engines, and that has to be pushed by appropriate incentives.

Energy efficiency policies will need to come in many shapes and forms.

- R&D to maintain a high rate of energy efficiency improvements in fossil technologies, continued R&D will be required. This R&D effort will be partly funded by the private sector as increasing requirements for energy efficiency and emission intensity will force corresponding investments. However, as fossil technologies become more and more uncompetitive, governments will need to provide financial support to ensure continuation of R&D efforts.
- Policies for low-carbon technologies, as the initial adoption is normally limited by two factors: high upfront costs and lack of supporting infrastructure. Policies aiming to support low-carbon technologies will need to address these issues by firstly supporting R&D to kick-start the positive feedback loop that results in cost reduction as a result of accumulated experience, and then forgoing tax revenue from the sales and use of these technologies, and finally by ensuring access to low-interest financing or even subsidizing by direct financial support. In some countries, government spending will be needed to cover or support the cost of some support infrastructure like power grids, smart meters, and EV charging.
- Passive policies like mandates, bans and stricter standards will continue to be important tools for governments to push energy efficiency, but quick and widespread adoption of these policies in the net zero future will require active financial support to overcome the burden of affordability.

Investments

In addition to the R&D spending needed to develop more efficient engines and boilers, significant investment levels are required to replace the existing stock of fossil-burning cars, trucks, stoves, boilers at rates faster than natural replacement rates. There is a huge energy saving potential to be realized by improving insulation of the building stock, especially in developing countries. In regions like South East Asia, the Indian Subcontinent and Sub-Saharan Africa, the majority of buildings that will be occupied in 2050 are yet to be built. Enforcing better building standards on these new buildings will be key to reducing energy consumption, especially when it comes to space cooling. In OECD countries, these upgrades will be costlier but equally crucial. From a building lifetime perspective, some of these investments will result in savings higher than the upfront cost.

Private sectors and governments will need to make infrastructure investments to support the adoption of energy-efficient technologies. Such investments involve EV charging infrastructure, hydrogen transmission and distribution networks, district heating pipelines, and power grids. Although these investments will be a crucial part of energy efficiency improvements, it is not easy to assess how much of these investments could be directly linked to required energy efficiency improvements.

3.12 COMPARISON OF THE SECTORS

Figure 3.23 shows the evolution of CCS capture rates in selected sectors from 2019 to 2050. 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 and therefore remains near zero within our 2050 timeframe.

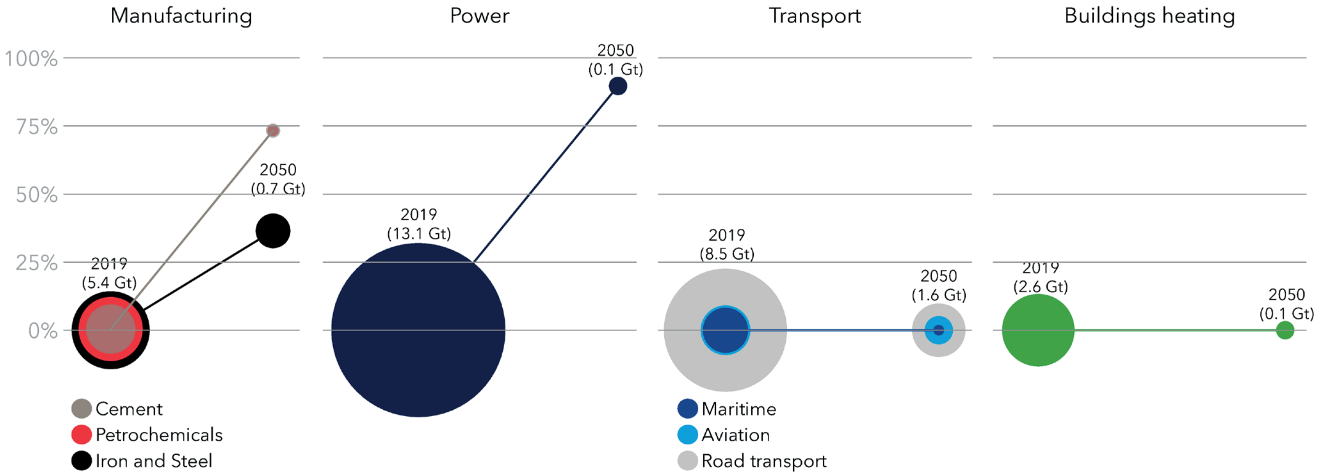
Furthermore, the area of the sector-specific concentric circles reveals that the greatest reduction of absolute emissions happens in the power sector, from 13.1 Gt down to 0.1 Gt, thanks to the very high uptake of CCS. In buildings, despite the lack of CCS, we still see a substantial decline in emissions thanks to electrification, from 2.6 Gt down to 0.1 Gt. In transport, although emissions are brought down significantly, we are still left with 1.6 Gt of emissions from hard-to-abate transport segments, such as long-haul trucking, aviation and maritime.

Figure 3.24 similarly has the CCS capture rate on the y-axis but shows sectoral emission intensities in 2050 on the x-axis. This visualization shows that by 2050, particularly challenging sectors will be those on the far-right lower corner, with high emission intensities and low CCS capture rates, i.e., road transport and aviation, as well as iron and steel. Buildings heating and maritime transport do not lend themselves to CCS capture, but decarbonization is achieved through electrification and fuel-switching in these sectors, which enable fairly low emission intensities by 2050.

FIGURE 3.23

Evolution of CCS capture rate in selected sectors

Units: **Percentages**

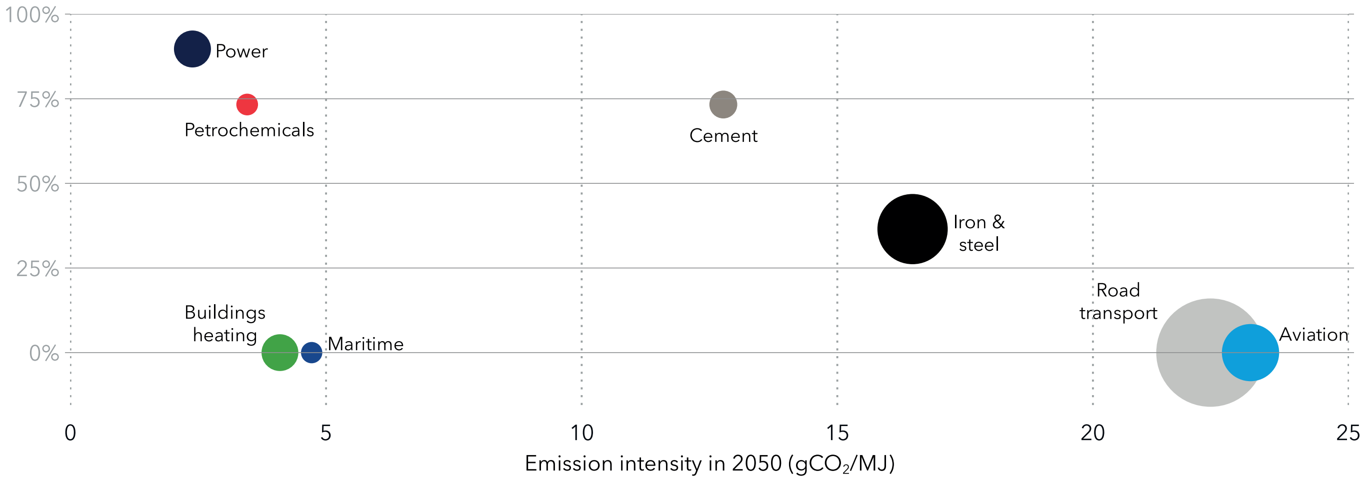


Bubble area is proportional to CO_2 emissions. Sectors are superimposed. In brackets: total CO_2 emissions

FIGURE 3.24

CO_2 emissions of selected sectors by 2050

Units: Percentages of emissions captured with CCS



Bubble area is proportional to emissions in 2050.

4 REGIONAL ROADMAPS

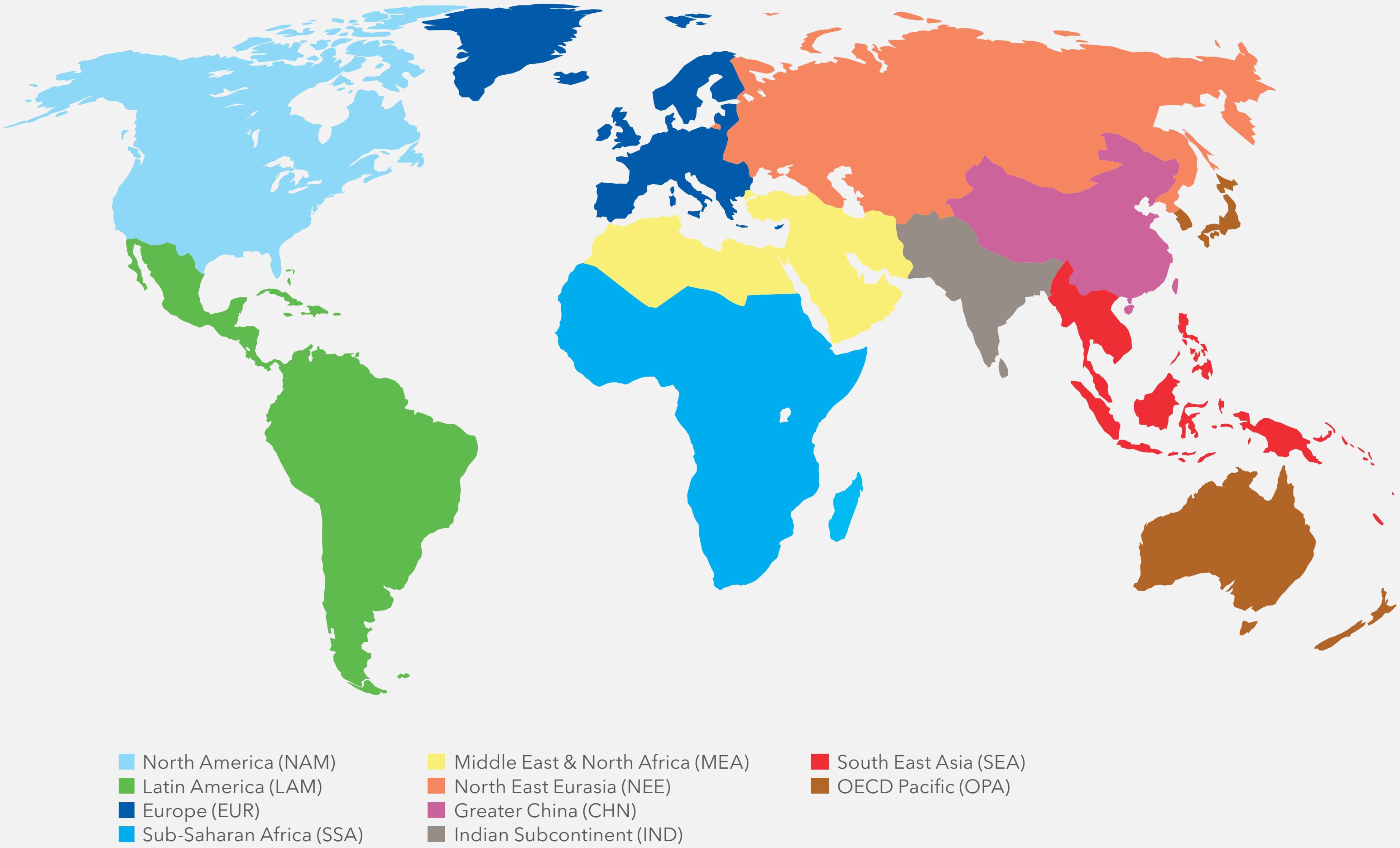
Global emissions and the regional picture

Countries and regions have very different starting points regarding available resources and existing energy-sector infrastructure, and in terms of human development. In our PNZ, we emphasize that the ten world regions will move at different paces towards their net zero destinations, and the developed regions will get there before 2050.

This does not imply that a region should delay its efforts to reduce emissions. To the contrary. We believe it is in every region's best interest to advance their development and economies, while *not* increasing emissions in tandem. The technologies available today make this possible and offer large potential for leapfrogging costly, polluting energy provision, production, and transport. All regions also need to adapt their economies to the effects of climate change, and enhance their trade-climate readiness (WEF, 2021) with global trade relations seeing adoption of carbon-border adjustment mechanisms.

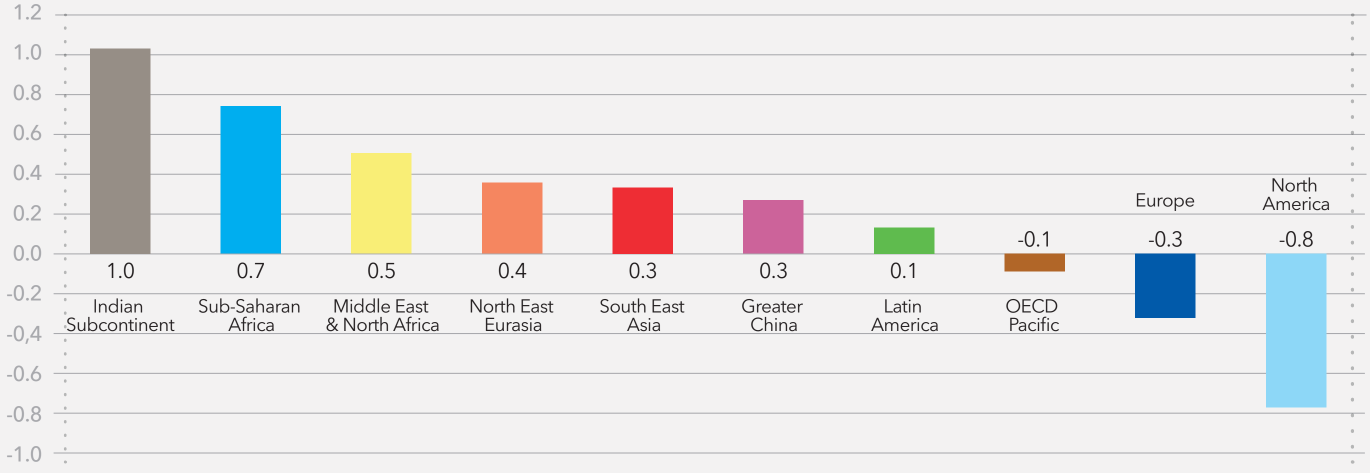
Nevertheless, we believe that high GDP regions with more advanced economies will – and should – move faster and carry more of the weight in enabling a net zero future (see discussion also in Section 1.5 Net zero policies). This applies particularly to ensuring progress in the development of key decarbonization solutions, which are currently less mature and significantly more expensive than today's conventional technology; the key is to accelerate the commercial readiness of these solutions for the world at large.

In this chapter, we describe the pathways to net zero for the ten world regions. In each of the regional sections, the PNZ of the main sectors of transport, buildings, manufacturing, and energy supply are briefly explained. For detailed information regarding policies implemented in each sector, please refer to Chapter 3 Sector roadmaps: Transport – Sections 3.1 to 3.3, Buildings – Section 3.4, Manufacturing – Sections 3.5 to 3.7 and Energy Supply – Sections 3.8 and 3.9.



2050 Energy-related CO_2 emissions after CCS and DAC

Units: $GtCO_2/yr$



NORTH AMERICA (NAM)

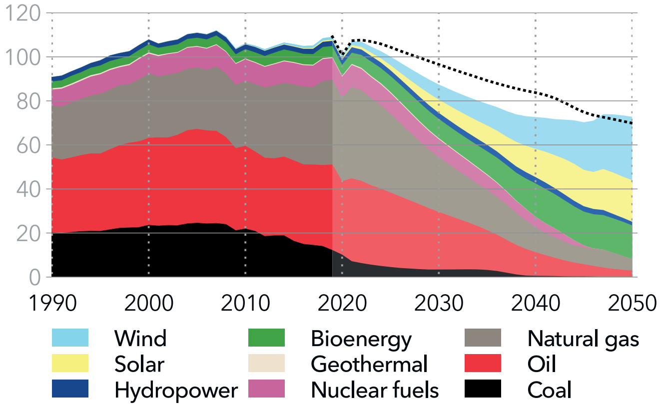
Region statistics		Population	GDP*	Energy use	Net CO_2 Emissions
2019	Overall	366 mn	22.6 trn	109 EJ	6.0 Gt
	Per capita		61 600	298 GJ	16.5 t
2050	Overall	437 mn	33.6 trn	73 EJ	-0.8 Gt
	Per capita		76 800	163 GJ	-1.8 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.1

North America primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.2

North America share of electricity and hydrogen

Units: Percentages

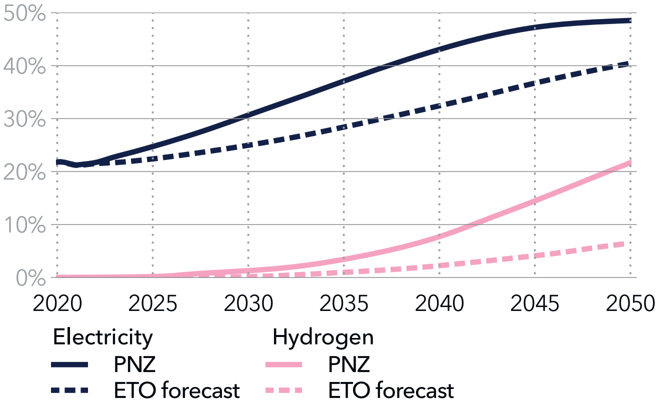
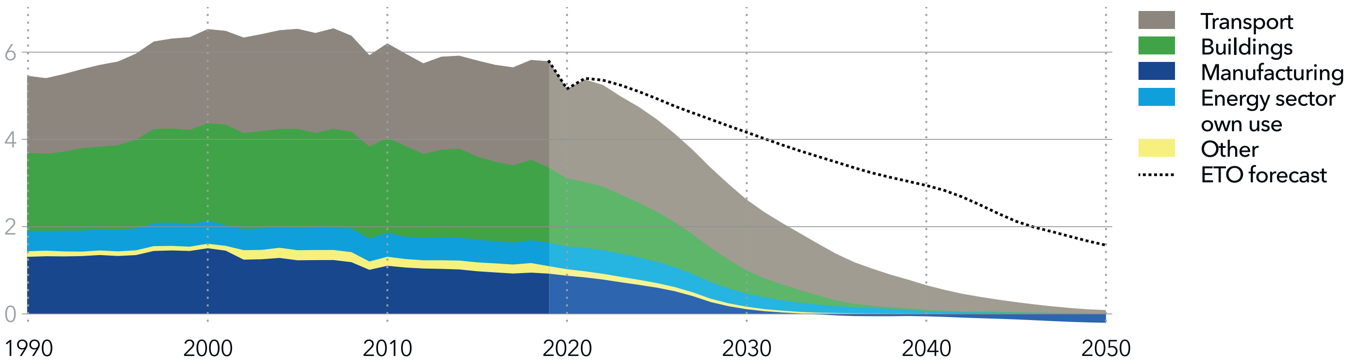


FIGURE 4.3

North America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

The PNZ for NAM sees CO_2 emissions reduce from 6 Gt in 2019 to -0.8 Gt by 2050 (Figure 4.3), with a rapid reduction in coal and oil, supplanted by electricity and hydrogen (Figure 4.2), in the energy system. Even in the PNZ, transport-sector emissions are the hardest to abate in NAM. The remaining oil in primary energy supply (Figure 4.1) is mostly used in the transport sector, and most natural gas use is abated with CCS and used in the non-energy and manufacturing sectors.

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 100/tCO_2 in 2030 and USD 250/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions reduce by 97% in NAM from 2019 to 2050 (Figure 4.3). This contrasts with the ETO where the equivalent reduction (2019-2050) was 77%. Such a decrease for PNZ is achieved by a two-pronged strategy for electrification of road transport in NAM, through subsidies for electricity for EVs and banning sales of fossil-fuel vehicles from 2030 for passenger vehicles and from 2040 for commercial vehicles, among others measures. While subsidies as high as 25% are given to electricity for EV propulsion, the fossil-fuel tax is increased by 100% in transport in 2050.

Buildings – CO_2 emissions fall by almost 100% in NAM from 2019 to 2050 (Figure 4.3). In the ETO, however, the equivalent reduction (2019-2050) was 74%. Three policy levers contribute here: better energy efficiency standards for new commercial and residential buildings' specific energy use (45% reduction in space heating and cooling), partial banning of fossil-fuel equipment (coal, oil, and gas) in buildings, and accelerated phase-out of fossil-fuel equipment by halving lifetimes (from 15 to 7.5 years) of new equipment.

Manufacturing – CO_2 emissions reduce to -0.2 Gt in NAM in 2050, which stands in contrast to our ETO where the reduction was to 0.38 Gt by 2050. The PNZ reduction is achieved by investment support to electrification of heat supply in the manufacturing sector, specifically a 10% support, starting from 2022 of the investment cost of industrial electric heat boilers and heat pumps. Similarly, a 50% support of electric and hydrogen capacity investments in the steel production are given from 2022.

Energy supply – CO_2 emissions from energy supply are reduced by bans on fossil fuel power plants from 2040 in NAM. Similarly, a 20% cost of capital for coal power plants from 2025, and a 17% cost of capital for oil and gas power plants also eliminate these power plants from the electricity grid.

Ambitions for emissions reduction

Both the Canadian and US governments have net zero GHG targets for 2050. Whereas the US aims for dropping below 50-52% of 2005 levels by 2030, Canada aims for a reduction of 40-45%. The Canadian target is enshrined in the Net-Zero Emissions Accountability Act (June 2021).

Concretization of net zero implementation plans and policy measures are in progress. Examples are Canada's climate plan: A Healthy Environment and a Healthy Economy and its Net Zero Advisory Body (established in 2021); and the US Build Back Better Agenda and The Infrastructure and Jobs Act that focus on infrastructure, energy, and transportation to spur the path to net zero.

Besides domestic efforts, both federal governments are pursuing cooperative efforts to advance technology development and deployment, such as through the Mission Innovation, the Net-Zero Producers Forum, and the Global Methane Pledge. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

LATIN AMERICA (LAM)

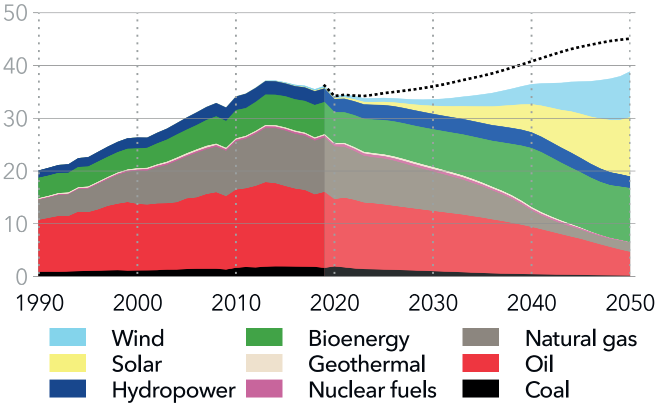
Region statistics		**Population**	**GDP***	**Energy use**	**Net CO_2 Emissions**
2019	Overall	657 mn	10.7 trn	36 EJ	1.9 Gt
	Per capita		16 100	55 GJ	2.9 t
2050	Overall	763 mn	22.7 trn	39 EJ	0.1 Gt
	Per capita		29 700	51 GJ	0.2 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.4

Latin America primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.5

Latin America share of electricity and hydrogen

Units: Percentages

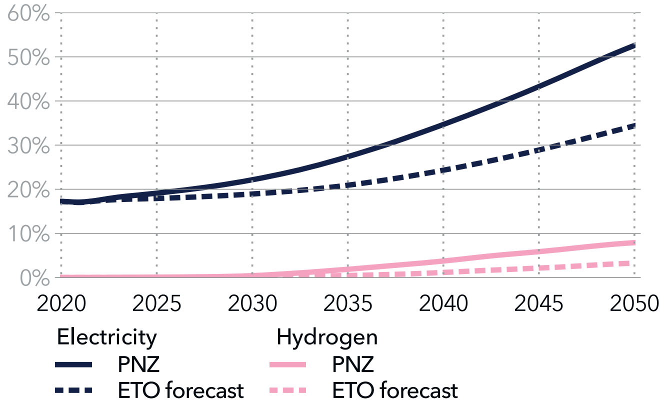
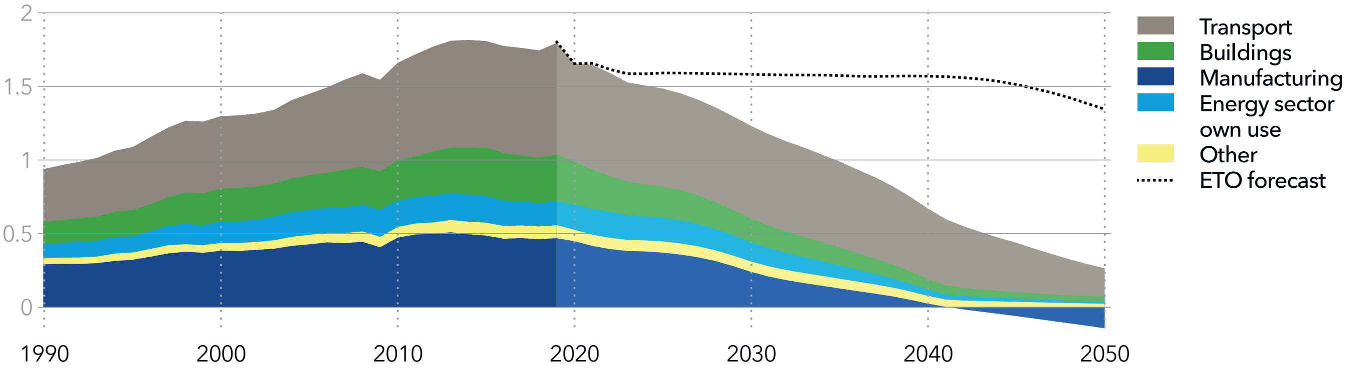


FIGURE 4.6

Latin America energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

The PNZ for LAM sees CO_2 emissions reducing from 1.9 Gt in 2019 to 0.1 Gt in 2050 (Figure 4.6). Although the manufacturing sector has negative emissions by using biomass and CCS, transport remains the sector with the highest net emissions in 2050. Electricity's share in final energy demand increases from 17% in 2019 to 53% in 2050; hydrogen's share rises from almost zero to 8% by 2050 (Figure 4.5). Half of the primary energy is supplied by solar and wind in 2050 (Figure 4.4).

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 50/tCO_2 in 2030 and USD 100/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – Transport sector emissions reduce by 75% from 2019 to 2050 in PNZ, in contrast to the 20% reduction in our ETO. This steep reduction in emissions is partly achieved by completely banning the sale of internal combustion engine (ICE) passenger vehicles in 2044, with restrictions on sale of ICE commercial vehicles beginning in 2043. Simultaneously, electricity for vehicle propulsion is subsidized by 10% of its average price from 2022, thus incentivizing investments in EVs.

Buildings – CO_2 emissions from buildings reduce by 88% from 2019 to 2050, in contrast to a 38% reduction in ETO. A partial ban of new fossil-fuel equipment for buildings, along with a subsidy of 10% of the electricity price for buildings, drives these reductions. Additionally, a higher cost of capital for fossil-fuel (17% for oil and natural gas, 20% for coal) equipment of commercial buildings also deters investment and locking-in of these technologies, while reducing emissions.

Manufacturing – Multiple policy levers reduce CO_2 emissions to -0.14 Gt by 2050 in a PNZ in LAM. Electricity and hydrogen as energy carriers are subsidized by 10% compared to their average price, and biomass is subsidized by 30%. Similarly, the capacity cost of electric heaters (including heat pumps) is supported by 4% from 2022. The share of electric arc furnace (EAF) in steel production increases to 90% by 2050, which also drastically reduces the consumption of coal in the manufacturing sector.

Energy supply – The increasing cost of capital for coal, oil, and natural gas power plants, among other policy levers, leads to elimination of CO_2 emissions from the power sector by 2050. Additionally, a gradual reduction in the cost of capital of non-fossil power plants also catalyzes investments into renewable power plants. More importantly, the support for storage capacity investments also rises, which encourages investments into VRES. All the hydrogen required for energy purposes is produced through electrolysis from 2028. Furthermore, investments into oil and gas capacity additions in the region are banned from 2028.

Ambitions for emissions reduction

The net zero agenda is present in the region. Chile's draft Climate Change Framework Law targets carbon neutrality by 2050. Argentina, Brazil, Columbia, Costa Rica, and Panama, have pledges, but they are not yet set in law. Mexico and Peru have targets under discussion (ECIU, 2021). Uruguay targets carbon neutrality as early as 2030, but, again, this aim is not enshrined in law.

In most LAM countries, sectoral implementation plans have yet to be developed. With rich natural resources, the region is well-endowed for energy system decarbonization. Land-based mitigation measures will also be in focus (e.g., Brazil's pledge to eliminate illegal deforestation by 2030).

Cooperative initiatives exist, e.g., the Renewable Energy for Latin America and the Caribbean (RELAC) Initiative's region goal of 70% renewable electricity by 2030. Argentina and Mexico have joined the Global Methane Pledge. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

EUROPE (EUR)

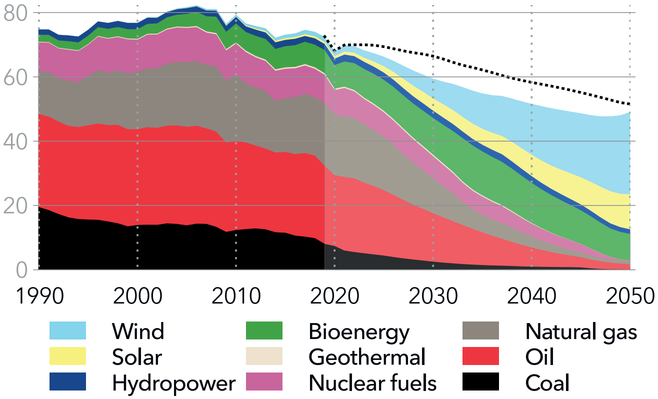
Region statistics		**Population**	**GDP***	**Energy use**	**Net CO_2 Emissions**
2019	Overall	545 mn	22.9 trn	72 EJ	3.7 Gt
	Per capita		42 000	133 GJ	6.7 t
2050	Overall	542 mn	31.5 trn	49 EJ	-0.3 Gt
	Per capita		58 100	91 GJ	-0.6 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.7

Europe primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.8

Europe share of electricity and hydrogen

Units: Percentages

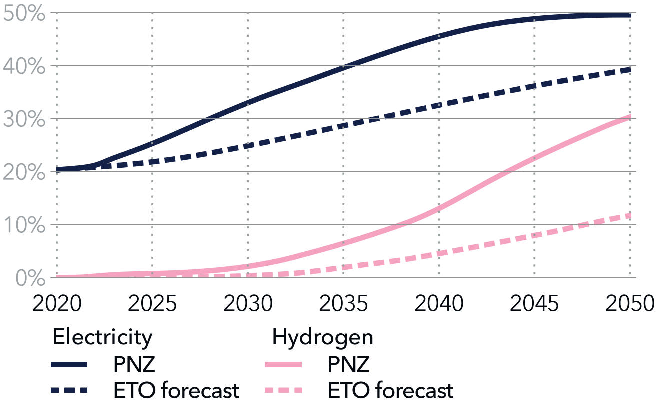
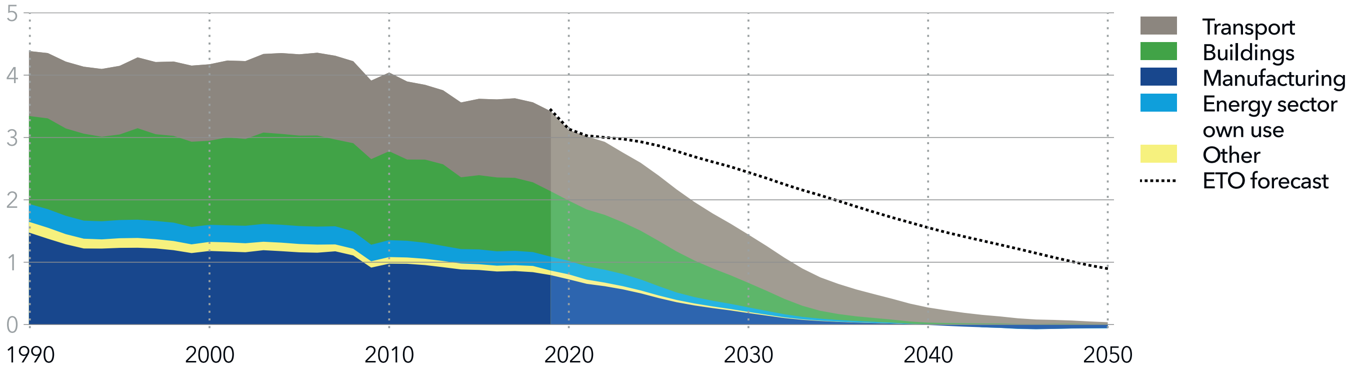


FIGURE 4.9

Europe energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

The PNZ for EUR sees CO_2 emissions dropping from 3.7 Gt in 2019 to -0.05 Gt by 2050 (Figure 4.9), and to -0.3 Gt with DAC. EUR has the highest ambitions to achieve a PNZ, which also translates to having the highest carbon price in comparison with all other regions in our PNZ. About 80% of the final energy demand is provided by electricity and electrolysis-based hydrogen by 2050 (Figure 4.8). Oil, as the major fossil fuel remaining in 2050 (Figure 4.7), is used in the non-energy sector.

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 150/tCO_2 in 2030 and USD 250/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions reduce 98% from 2019 to 2050 in EUR; this is a greater decrease than in ETO, where a reduction of 81% was seen for the corresponding period. EUR bans the sale of ICE vehicles in both passenger and commercial segments from 2035. In our PNZ, EUR, along with OPA, has the most stringent policy measures in road transport, in tandem with subsidized electricity prices for EV propulsion.

Buildings – CO_2 emissions reduce to zero, or to slightly positive emissions, by 2050, while in the ETO the reduction from 2019 to 2050 was 53%. The reductions in CO_2 are achieved because of a mandated partial ban of 50% on fossil-fuel equipment in buildings by 2050. Likewise, the lifetime of new fossil-fuel equipment halves (from 15 to 7.5 years), which also enables a faster phase-out of fossil fuel. Commercial buildings also face higher cost of capital if they have fossil-fuel equipment.

Manufacturing – CO_2 emissions in the manufacturing sector in EUR reduce to -57 Mt by 2050, again due to emissions being captured from biomass combustion. Electricity and hydrogen both have capacity investment support of 50% for iron ore reduction in EUR, along with a 100% share of EAF in steel production in 2050. Electricity-based heating is incentivized by a subsidy of 10% of the electricity price, while a tax of 25% is added on top of fossil-fuel price, assisting the transition to biomass.

Energy supply – CO_2 emissions from the power sector reduce to -40 Mt by 2050, with negative emissions achieved due to biomass-fired power plants. Oil and gas capacity additions are banned from 2024, followed by a faster ramp up rate for CCS, which enables the production of blue hydrogen. Concurrently, grid electricity is subsidized when used for hydrogen production, in addition to the capacity investment support of 25% for dedicated renewables for hydrogen production. Despite this, the region continues to produce blue hydrogen until it narrows to a share of just 0.1% in 2050.

Ambitions for emissions reduction

The EU targets of 55% cuts below 1990-levels by 2030 and net zero GHG emissions by 2050 were agreed upon in December 2020. The objective of a climate-neutral EU by 2050 is binding, enshrined into the European Climate Law of June 2021.

Several EU members have faster and higher decarbonization ambitions e.g., Germany 65% and Denmark 70% by 2030, and Sweden for net zero GHG emissions by 2045. Outside the EU, the UK aims to reduce emissions by 68% by 2030 and 78% by 2035 (compared with 1990-levels), with targets set in law in 2019.

Among all regions, EUR has progressed the furthest in backing up its pledges with net zero implementation plans and strengthening policies. Examples are the Green Deal, the 'Fit for 55' Package, and the EU Taxonomy regulation to redirect investment flows in alignment with objectives; and all EU members developing national long-term strategies, covering GHG reductions/removals, with a 30-year perspective. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

SUB-SAHARAN AFRICA (SSA)

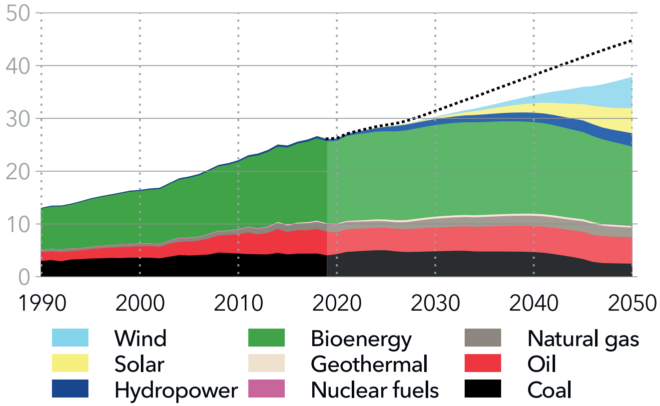
Region statistics		**Population**	**GDP***	**Energy use**	**Net CO_2 Emissions**
2019	Overall	1.11 bn	4.5 trn	26 EJ	1 Gt
	Per capita		4 000	23 GJ	0.9 t
2050	Overall	1.99 bn	18.4 trn	38 EJ	0.7 Gt
	Per capita		9 200	19 GJ	0.4 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.10

Sub-Saharan Africa primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.11

Sub-Saharan Africa share of electricity and hydrogen

Units: Percentages

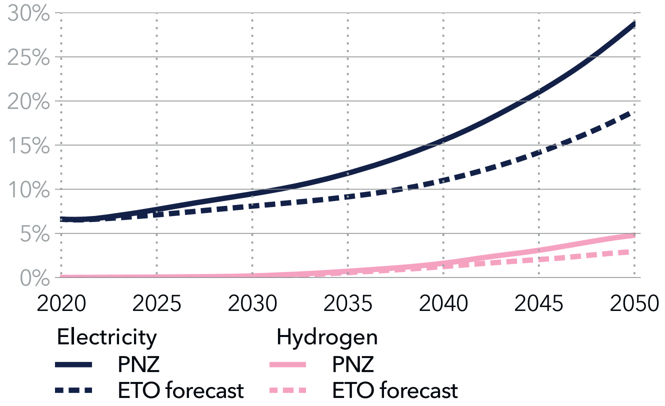
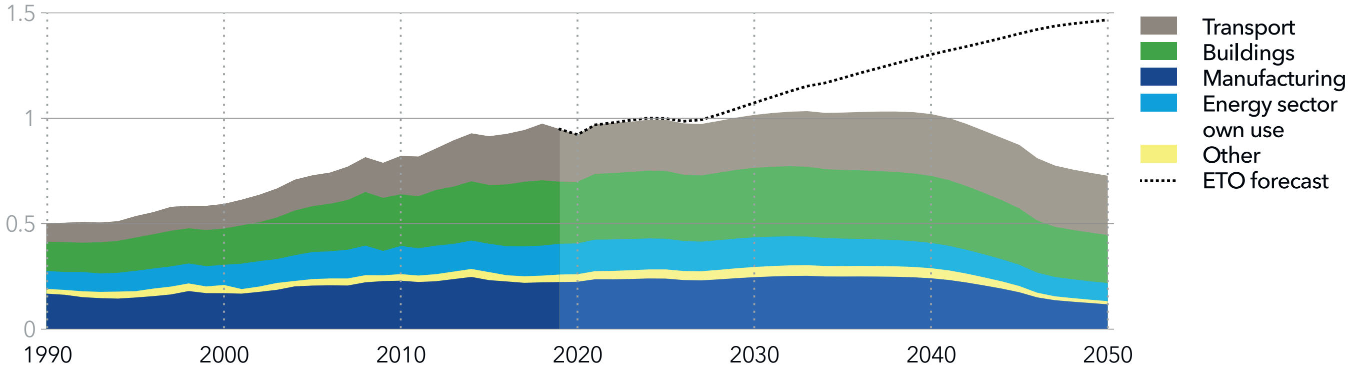


FIGURE 4.12

Sub-Saharan Africa energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

The PNZ for SSA sees CO_2 emissions dropping from 1 Gt to 0.7 Gt by 2050 (Figure 4.12). Regionally, the CO_2 emissions of SSA are behind that of only IND. Given the historically low emissions from this region, this is justified for our PNZ. The critical point to note is that the region largely leapfrogs fossil fuel intensive infrastructure (Figure 4.10).

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 15/tCO_2 in 2030 and USD 50/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions increase slightly, rising from 250 Mt in 2019 to 280 Mt by 2050. This is not surprising as transport policies adopted in SSA are the least stringent, with no bans on the sale of ICE vehicles, unlike in other regions. This also because the necessary charging infrastructure for electrification of transport is not yet present and will take longer time to come into existence in the region. Transport still remains a hard-to-abate sector in our PNZ for SSA.

Buildings – CO_2 emissions reduce by 23% from 2019 to 2050. This is achieved through partial bans (25%) on fossil fuel equipment in buildings by 2050. Additionally, the lifetime of new fossil-fuel equipment in buildings halve (from 15 to 7.5 years), and traditional biomass equipment similarly has only half the previous lifetime. This enables faster electrification of buildings, rising from 5% in 2019 to 22% in 2050. Commercial buildings also face higher cost of capital if they have fossil-fuel equipment.

Manufacturing – CO_2 emissions reduce by 47% from 2019 to 2050 in the manufacturing sector. The cost of capital of oil and gas equipment in the manufacturing sector increases from 8% in 2022 to 17%, and the cost of capital of coal equipment increases to 20%. This considerably reduces the attractiveness of fossil-fuel equipment in the PNZ, enabling the faster-phaseout of these.

Energy supply – CO_2 emissions from the power sector reduce to 8 Mt, from 2019 to 2050. This decrease occurs with the share of electricity in final energy demand rising from 7% to 29% (Figure 4.11). Similarly, hydrogen grows from having no share in 2019 to 5% in 2050. New oil and gas capacity additions are banned from 2028. Grid electricity is subsidized when used for hydrogen production, in addition to the capacity investment support of 10% for dedicated renewables for hydrogen production.

Ambitions for emissions reduction

Regional ambitions from nationally determined contributions (NDCs) suggest a regional target for emissions to grow by no more than 174% by 2030 relative to 1990. Looking ahead to 2050, very few SSA countries have adopted targets to reduce emissions.

South Africa has a net zero target by 2050 (Government of South Africa, 2020) and its Climate Change Bill, due in parliament later this year (MG, 2021). Its updated NDC (September 2021) puts the power sector in focus during the 2030s, coupled with low-emission vehicles in transport, and decarbonization of hard-to-abate sectors targeted over the 2040s. These are all based on continued effective multilateral cooperation.

The region is on a development trajectory, focusing on human-development outcomes and economies that depend on energy systems evolving. Promised global finance and technology transfer will be important for countries of the SSA region to pursue low-emission development strategies. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

MIDDLE EAST AND NORTH AFRICA (MEA)

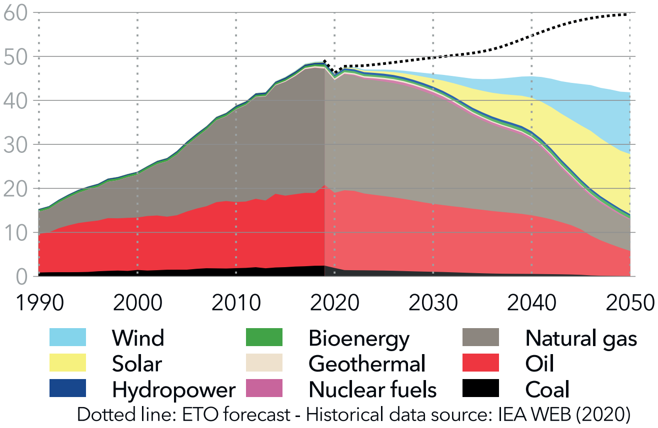
Region statistics		Population	GDP*	Energy use	Net CO_2 Emissions
2019	Overall	539 mn	11.2 trn	49 EJ	3.7 Gt
	Per capita		20 600	91 GJ	6.9 t
2050	Overall	728 mn	25.6 trn	42 EJ	0.5 Gt
	Per capita		35 000	57 GJ	0.7 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.13

Middle East and North Africa primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.14

Middle East and North Africa share of electricity and hydrogen

Units: Percentages

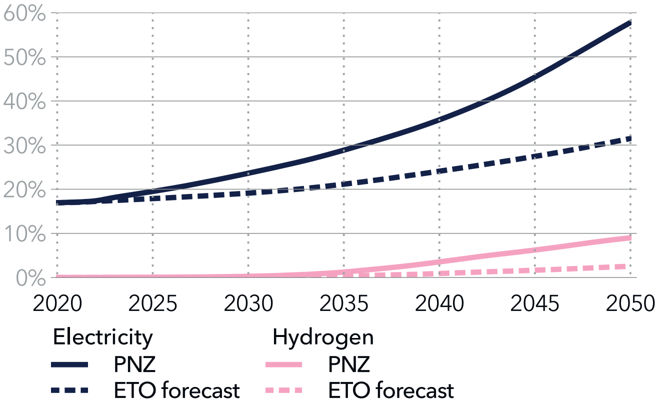
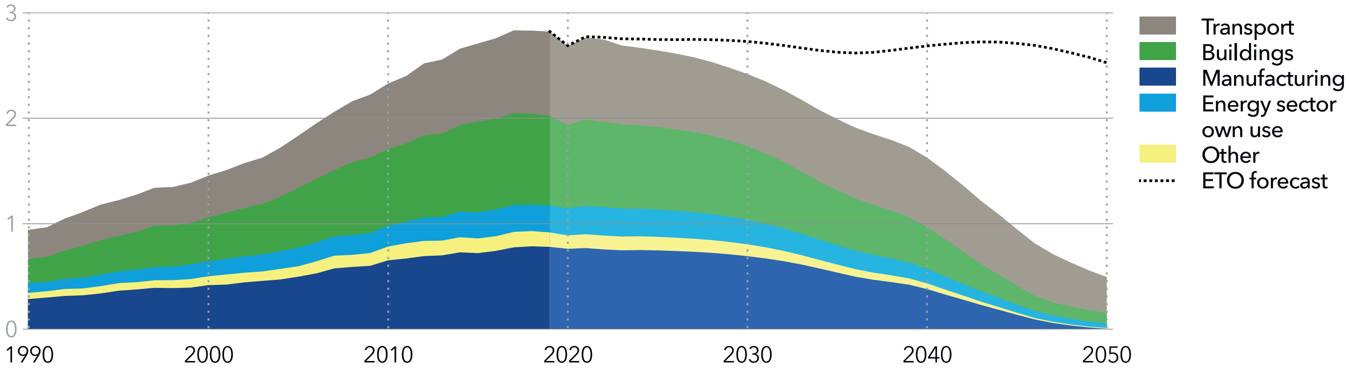


FIGURE 4.15

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

Units: $GtCO_2$/yr



Net zero pathway

CO_2 emissions reduce from 3.7 Gt in 2019 to 0.5 Gt in 2050 in MEA (Figure 4.15). This is achieved by breaking away from the use of indigenous oil and gas. Our PNZ sees MEA departing from using its domestic oil and gas, especially in the transport sector, partly because of an increasing carbon price, but also in response to mounting pressure to abate, due to high emissions in the past. Nevertheless, considerable natural gas remains in the system, especially in manufacturing and buildings (Figure 4.13). While some grey hydrogen remains, which is used as feedstock, all the hydrogen used as an energy carrier is produced from electrolysis from 2029 (Figure 4.14).

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 30/tCO_2 in 2030 and USD 100/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions reduce by 58% from 2019 to 2050. This contrasts with the ETO, where an increase of 12% was seen for the corresponding period. Despite its vast domestic resources, and lower fuel prices, there is a ban on the sale of new ICE vehicles from 2045 for passenger vehicles and 2050 for commercial vehicles. Concurrently, the tax on oil price for transport rises by 200% in 2050, albeit from a low base.

Buildings – CO_2 emissions reduce by 88% from 2019 to 2050 whereas in our ETO the equivalent reduction was 24%. All oil and natural gas subsidies for buildings are eliminated from 2022. Simultaneously, a partial ban of 25% on all new fossil-fuel equipment in buildings is implemented by 2050. These two policy levers, along with the lifetime of new fossil-fuel equipment being halved (from 15 to 7.5 years), contribute to the emission reductions.

Manufacturing – In the manufacturing sector, CO_2 emissions reduce to 36 Mt by 2050. The cost of capital of oil and gas equipment in the manufacturing sector increases from 8% in 2022 to 11% in 2050, while the cost of capital of coal equipment increases to 20%. Simultaneously, an investment support of 4% is given to electric heat production. This considerably reduces the attractiveness of fossil-fuel equipment in the PNZ, enabling faster phase-out of these.

Energy supply – CO_2 emissions from the power sector reduce from 1 Gt in 2019 to zero by 2050. This occurs while the share of electricity in final energy demand simultaneously grows from 17% in 2019 to 58% by 2050. Hydrogen's share grows from nearly zero to 9% by 2050 (Figure 4.14). New oil and gas capacity additions are banned from 2028. Concurrently, grid electricity is subsidized when used for hydrogen production, in addition to the capacity investment support of 10% for dedicated renewables for hydrogen production.

Ambitions for emissions reduction

Paris Agreement commitments have focused on restricting emissions by 2030, compared to business-as-usual scenarios, and from many countries in the MEA region, this is conditional on international support.

Recent (2021) announcements have a 2050-time horizon. The United Arab Emirates, the first among the region's petrostates, has announced a strategic initiative committing to achieve net zero GHG emissions by 2050, possibly leading others in the Persian Gulf to follow suit. Israel aims to cut GHG emissions by 85% in 2050, relative to 2015. Turkey, the last G20 country to ratify the Paris Agreement (October 2021), also announced a net zero goal by 2053. Egypt's Vision 2030 is imminent and interest in hosting COP27 in 2022 has been expressed.

Domestic efforts are being made, but needs detailing of sectoral implementation plans. Internationally, Iraq has indicated its support for the Global Methane Pledge, and Qatar has joined the Net-Zero Producers Forum. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

NORTH EAST EURASIA (NEE)

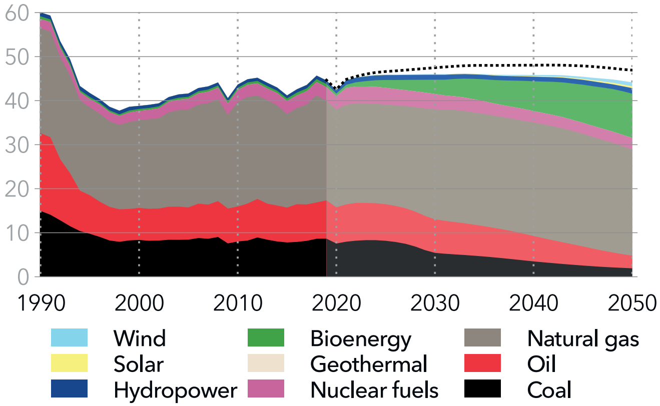
Region statistics		**Population**	**GDP***	**Energy use**	**Net CO_2 Emissions**
2019	Overall	319 mn	5.7 trn	45 EJ	3.0 Gt
	Per capita		18 000	140 GJ	9.4 t
2050	Overall	316 mn	11.3 trn	44 EJ	0.4 Gt
	Per capita		35 900	140 GJ	1.1 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.16

North East Eurasia primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.17

North East Eurasia share of electricity and hydrogen

Units: Percentages

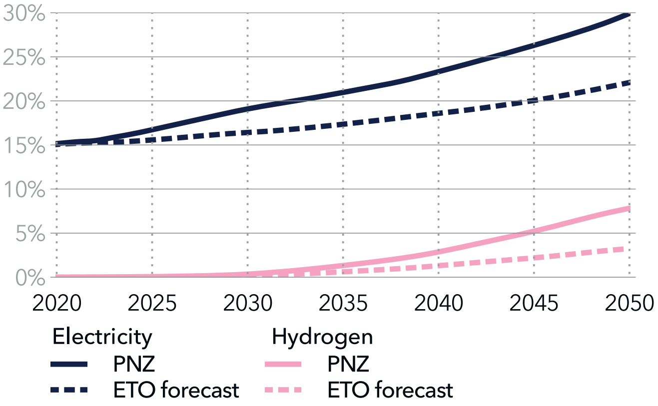
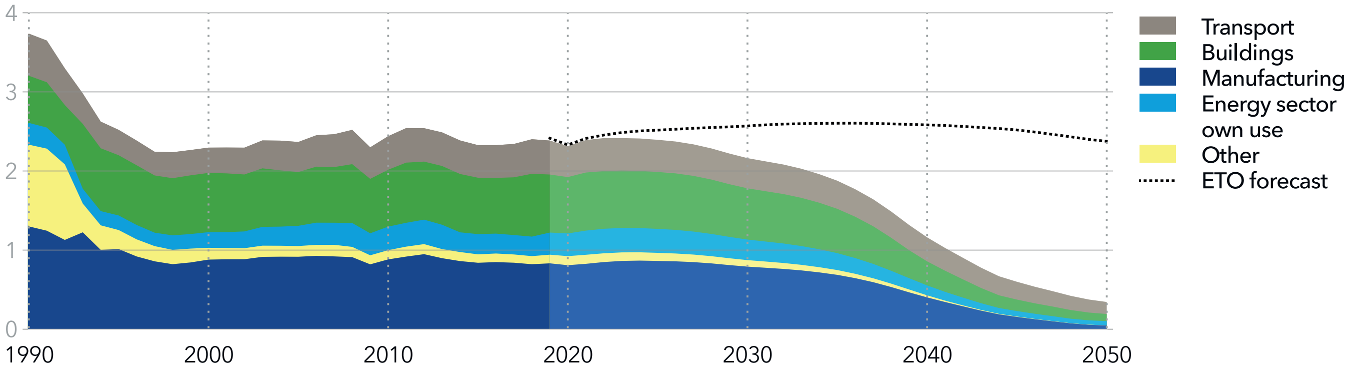


FIGURE 4.18

North East Eurasia energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

CO_2 emissions reduce from 3 Gt in 2019 to 400 Mt by 2050 (Figure 4.18). NEE is the region with the highest per capita CO_2 emissions in 2050. Considerable use of natural gas remains in the system (Figure 4.16), the majority of which is used in the non-energy sector and for abated power generation and blue hydrogen production. Although NEE achieves some abatement of emissions by the use of CCS coupled with biomass, this is nowhere near enough to achieve net zero.

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 30/tCO_2 in 2030 and USD 100/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions reduce by 65% from 2019 to 2050. This contrasts with the ETO, where a reduction of 2% was seen for the corresponding period. Despite its vast domestic hydrocarbon resources, and lower fuel prices, sale of new ICE vehicles is banned from 2045 for passenger vehicles and 2050 for commercial vehicles. Concurrently, the tax on oil price for transport is 200% in 2050, albeit from a low base.

Buildings – CO_2 emissions reduce from 0.7 Gt in 2019 to 0.1 Gt by 2050; in the ETO the emissions were 0.9 Gt. A partial ban of 25% on all fossil-fuel equipment in buildings is implemented by 2050, and the lifetime of new fossil-fuel equipment is halved (from 15 to 7.5 years). These two policy levers contribute to the reduction in emissions by enabling faster phase-out of fossil fuel infrastructure. Similarly, through biomass coupled with CCS, NEE also achieves negative emissions from direct heat for its buildings.

Manufacturing – CO_2 emissions in the manufacturing sector reduce from 0.9 Gt in 2019 to 50 Mt by 2050. The cost of capital of oil and gas equipment in the manufacturing sector increases from 8% in 2022 to 11% in 2050, and the cost of capital of coal equipment increases to 20%. Simultaneously investment support of 4% is given to electric heat production. This considerably reduces the attractiveness of fossil-fuel equipment in the PNZ, enabling the faster phase-out.

Energy supply – CO_2 emissions from the power sector reduce from 1.1 Gt in 2019 to 0.1 Gt by 2050. This occurs while simultaneously with growth in the share of electricity in final energy, rising from 15% in 2019 to 30% in 2050 (Figure 4.17). Similarly, hydrogen increases from very low levels to 8% by 2050. All new fossil fuel power capacity additions have reduced lifetimes (from 40 to 25 years), thus enabling a faster phase-out of fossil fuel use for power generation. New oil and gas capacity additions are banned from 2028. Concurrently, grid electricity is subsidized when used for hydrogen production, along with capacity investment support of 10% for dedicated renewables for hydrogen production.

Ambitions for emissions reduction

Interpretation of country NDC pledges in the NEE region suggests that the average regional target for reducing energy-related emissions is 26% by 2030, relative to 1990, with Russia aiming for cuts of around 30%. Looking ahead to 2050, few countries of the NEE region have adopted targets to reduce CO_2 emissions.

Russia, being dominant in size and economy, has faced pressure from the EUR region to make more ambitious commitments. The long-term strategy for 2050 that was originally proposed, effectively meant increasing emissions towards 2030 from today's levels, and declining thereafter due to more aggressive policies between 2028-2050. Peak emissions were to be reached in around 2030 and carbon neutrality achieved close to the end of the century (WRI, 2020).

However, an earlier net zero year is now under consideration with a new draft plan that aims to cut CO_2 emissions by 79% by 2050 with net zero emissions achieved by 2060. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

GREATER CHINA (CHN)

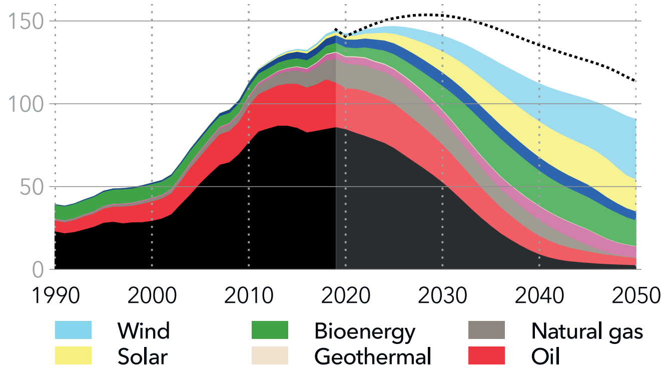
Region statistics		**Population**	**GDP***	**Energy use**	**Net CO_2 Emissions**
2019	Overall	1.44 bn	30.6 trn	145 EJ	11.8 Gt
	Per capita		21 200	100 GJ	8.1 t
2050	Overall	1.33 bn	65.1 trn	91 EJ	0.3 Gt
	Per capita		49 000	68 GJ	0.2 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.19

Greater China primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.20

Greater China share of electricity and hydrogen

Units: Percentages

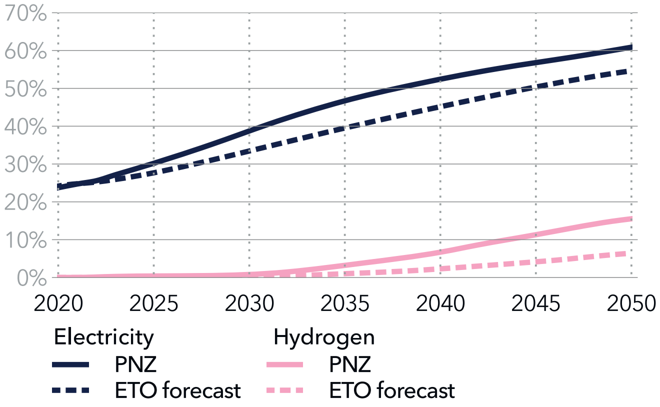
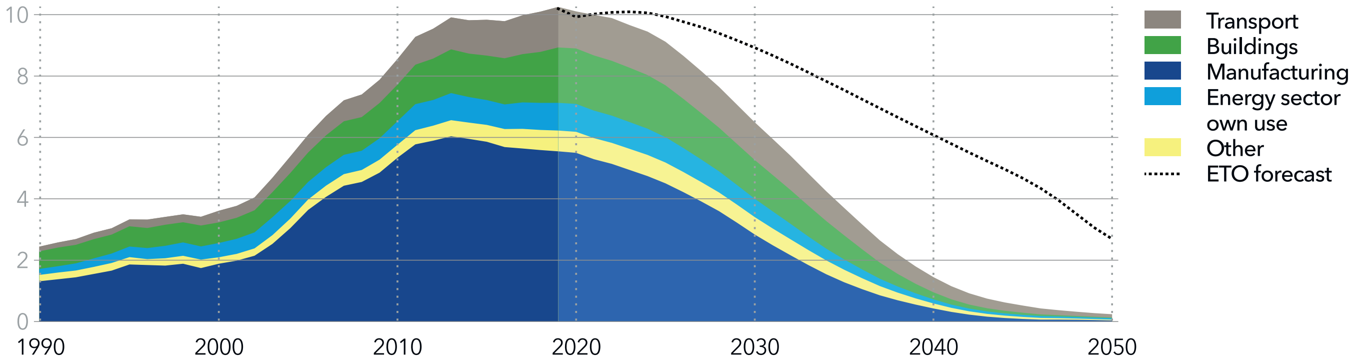


FIGURE 4.21

Greater China energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

Greater China's CO_2 emissions fall from 11.8 Gt in 2019 to 0.3 Gt in 2050 (Figure 4.21). Considering the size of both absolute and share of emissions from this region, compared with the rest of the world, it is imperative that CHN achieves net zero in order for the world to achieve net zero. A rapid decline in the use of coal (Figure 4.19), which is replaced by electricity and hydrogen, and fast uptake of CCS all contribute to this reduction in emissions.

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 100/tCO_2 in 2030 and USD 200/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions decrease by 92% from 2019 to 2050, which contrasts with the ETO, where a reduction of 64% was projected for the corresponding period. CHN institutes a ban on the sale of ICE vehicles (both passenger and commercial) from 2035, while subsidizing the electricity price by 20% from 2022.

Buildings – CO_2 emissions reduce from 1.8 Gt in 2019 to 20 Mt in 2050, while in the ETO the reduction was to 600 Mt. A partial ban of 50% on all new fossil-fuel equipment in buildings is implemented by 2050, while the lifetime of new fossil-fuel equipment is halved (from 15 to 7.5 years). These two policy levers contribute to the emission reductions by enabling faster phase-out of fossil fuel infrastructure.

Manufacturing – CO_2 emissions reduce from 5.5 Gt in 2019 to 35 Mt by 2050 in the manufacturing sector. The cost of capital of oil and gas equipment in the manufacturing sector increases from 8% in 2022 to 17%, while cost of capital of coal equipment increases to 20%. Simultaneously investment support of 20% is given to electric heat production. This considerably reduces the attractiveness of fossil-fuel equipment in the PNZ, enabling their faster phase-out of these.

Energy supply – CO_2 emissions from the power sector reduce from 4.5 Gt in 2019 to 22 Mt in 2050. All new fossil fuel power capacity additions have reduced lifetimes (from 40 to 25 years), thus enabling a faster phaseout of fossil fuel use for power generation. This reduction in emissions occurs while the share of electricity in energy demand grows from 23% in 2019 to 61% in 2050 (Figure 4.20). Similarly, the share of hydrogen grows from almost nothing to 16% by 2050. New oil and gas capacity additions are banned from 2028. Concurrently, grid electricity is subsidized when used for hydrogen production, in addition to the capacity investment support of 10% for dedicated renewables for hydrogen production. A 20% investment cost support is provided for renewable electricity battery storage, which further boosts the installation of VRES power plants.

Ambitions for emissions reduction

In September 2020, China announced that it will aim for emissions to peak before 2030 and be carbon neutral by 2060.

The carbon neutrality trajectory will be rooted in Five-Year Plans (FYP), connecting present policies to 2035 development goals, and continuing the transition to 2060. Over the 14th FYP (2021-2025) increases in coal consumption shall be limited, before coal use then phases down during 2026-2030. Carbon-emission intensity (tCO2 per unit GDP) shall decrease by more than 65% (from 2005) by 2030. Long-term decarbonization plans are under development. A national plan for peak emissions is imminent (winter/2021/22), and industry-specific plans will follow.

In addition to domestic efforts, China made the policy announcement to stop financing and building new coal-fired power plant overseas and promised to step up support backing developing countries in their pursuit of low-carbon futures. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

INDIAN SUBCONTINENT (IND)

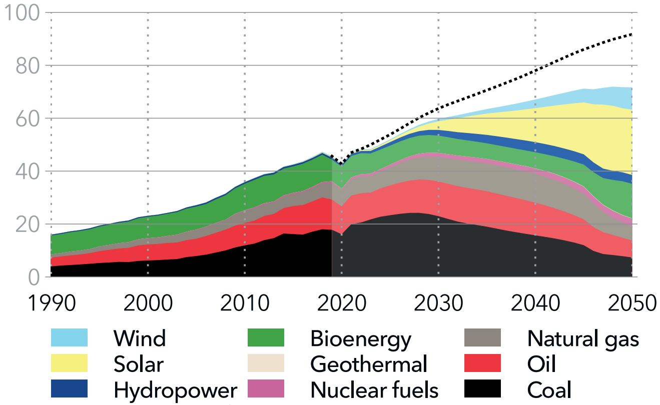
Region statistics		**Population**	**GDP***	**Energy use**	**Net CO_2 Emissions**
2019	Overall	1.83 bn	12.7 trn	46 EJ	2.8 Gt
	Per capita		6 900	25 GJ	1.5 t
2050	Overall	2.29 bn	48.2 trn	72 EJ	1.0 Gt
	Per capita		21 000	31 GJ	0.4 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.22

Indian Subcontinent primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.23

Indian Subcontinent share of electricity and hydrogen

Units: Percentages

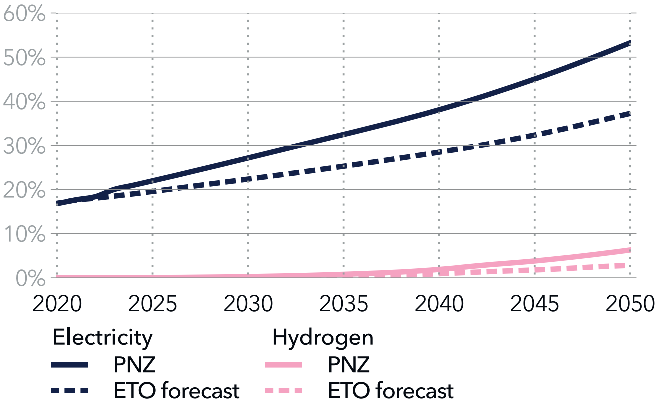
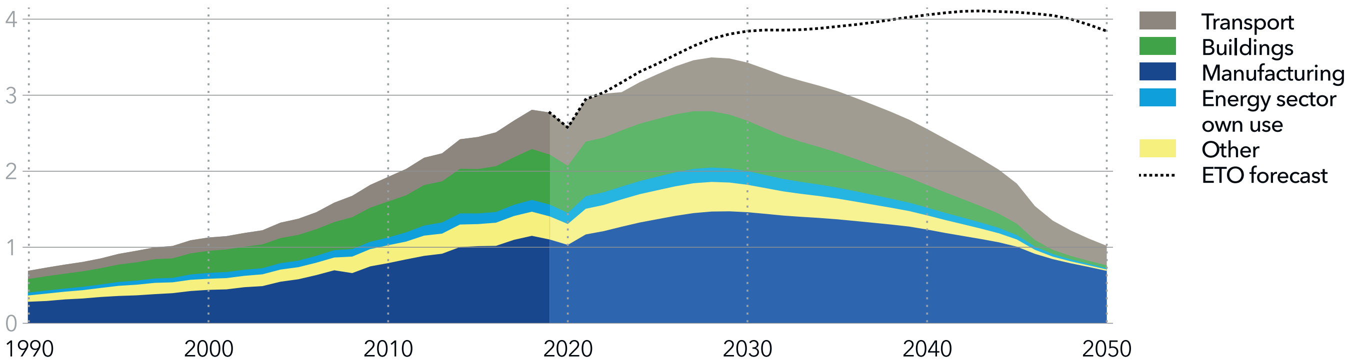


FIGURE 4.24

Indian Subcontinent energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

CO_2 emissions in the PNZ for IND reduce in the PNZ for 2.8 Gt in 2019 to 1.0 Gt in 2050 (Figure 4.24), driven by rapid penetration of renewables in primary energy (Figure 4.22). Despite this ramp up of renewables, substantial shares of natural gas (7%), coal (10%), and oil (9%) persist in the energy system in 2050. IND has the largest CO_2 emissions in 2050. Given its historically low emissions from the energy sector, it is vital that a PNZ helps the region phase out fossil fuel and avoid being locked-in to new fossil infrastructure.

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 30/tCO_2 in 2030 and USD 75/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions reduce by 54% from 2019 to 2050, while in the ETO the emissions grew by 100% in the corresponding period. IND institutes a ban on the sale of passenger ICE vehicles from 2041 and on commercial ICE vehicles from 2047 and subsidizes the transport electricity price by 8% from 2022.

Buildings – CO_2 emissions reduce from 0.6 Gt in 2019 to 36 Mt by 2050, while in the ETO, emissions were still 0.6 Gt. A partial ban of 25% on all new fossil-fuel equipment in buildings is instituted by 2050, and the lifetime of new fossil-fuel equipment is halved (from 15 to 7.5 years) from 2022. These two policy levers contribute to the reduction in emissions by enabling faster phase-out of fossil fuel infrastructure, and accelerating electrification of buildings.

Manufacturing – CO_2 emissions reduce from 1.1 Gt in 2019 to 0.7 Gt in 2050 in the manufacturing sector. The cost of capital of oil and gas equipment in the manufacturing sector increases from 8% in 2022 to 17%, while cost of capital of coal equipment increases to 20% in 2050. Concurrently, a 15% tax on coal price is levied in the manufacturing sector, further discouraging coal use. Investment support of 3% is given to electric and hydrogen heat production. These considerably reduce the attractiveness of fossil-fuel equipment in the PNZ, enabling faster phase-out of fossil-fuel technologies.

Energy supply – CO_2 emissions from the power sector reduce from 1.2 Gt in 2019 to 40 Mt by 2050. All new fossil fuel power capacity additions have reduced lifetimes (from 40 to 25 years), thus enabling faster phase-out of fossil fuel use for power generation. Simultaneously, the share of electricity in energy demand grows from 17% in 2019 to 53% by 2050 (Figure 4.23). New oil and gas capacity additions are banned from 2028 and, grid electricity is subsidized when used for hydrogen production. In addition, capacity investment supports of 7.5% are implemented for dedicated renewables for hydrogen production. Despite this, the share of blue hydrogen in hydrogen as an energy carrier is approximately 12% in 2050.

Ambitions for emissions reduction

Net zero targets are mostly still under consideration in the IND region. Sri Lanka has advanced its carbon-neutrality target to 2050 (originally set for 2060). India is committed to a large renewable energy expansion, and as a large emitter faces pressure to make commitments (Ahluwalia et al., 2021).

A regional driver towards adopting net zero ambitions is strategic green industrialization, availability of technology to decouple an increase in energy use from emissions and avoidance of locking-in energy systems to fossil fuels. Another driver is self-interest in effective climate action given the region's vulnerability to climate risk (Germanwatch, 2021)

The region is on a development trajectory, with focus on achieving human-development outcomes. In order to meet both development goals and emissions goals, global climate financing and technology transfer will be important for many countries in the region. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

SOUTH EAST ASIA (SEA)

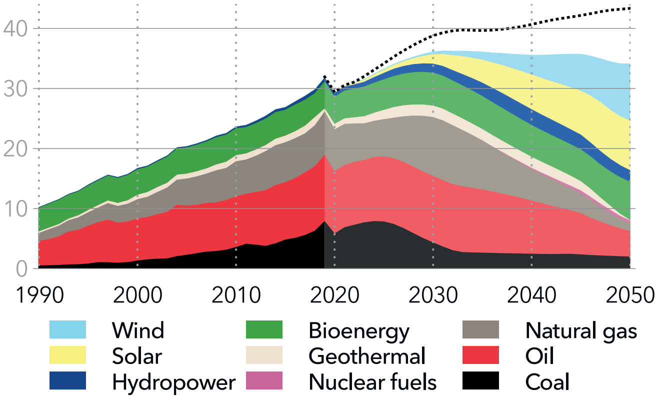
Region statistics		Population	GDP*	Energy use	Net CO_2 Emissions
2019	Overall	673 mn	9 trn	32 EJ	1.7 Gt
	Per capita		13 400	47 GJ	2.6 t
2050	Overall	783 mn	25.2 trn	34 EJ	0.3 Gt
	Per capita		31 200	44 GJ	0.4 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.25

South East Asia primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.26

South East Asia share of electricity and hydrogen

Units: Percentages

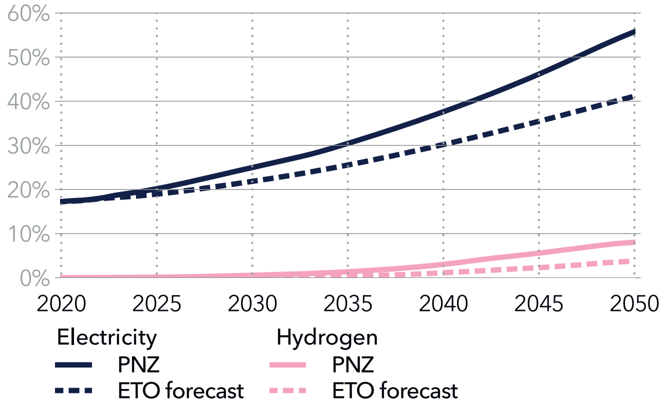
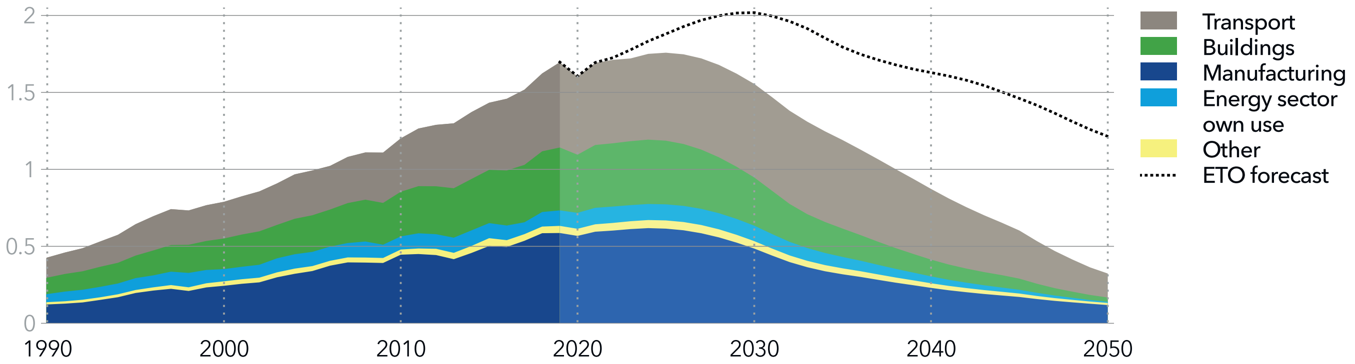


FIGURE 4.27

South East Asia energy-related CO_2 emissions by sector

Units: $GtCO_2$/yr



Net zero pathway

CO_2 emissions reduce from 1.7 Gt in 2019 to 0.3 Gt in 2050 in the PNZ for SEA (Figure 4.27), driven by rapid penetration of renewables and reductions in fossil fuel use (Figure 4.25). However, significant amounts of fossil fuels remain even in 2050, especially natural gas in power, coal in manufacturing, and oil in transport (accountable for 50% of emissions in 2050).

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 50/tCO_2 in 2030 and USD 100/tCO2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions reduce by 72% from 2019 to 2050 (150 Mt), which contrasts with our ETO, where a reduction of 8% was seen for the corresponding period. SEA implements a ban on sale of passenger ICE vehicles from 2040 and on commercial ICE vehicles from 2047 and subsidizes the transport electricity price by 10% from 2022. Despite these measures, there is still considerable oil use and makes transport emissions remain significant.

Buildings – CO_2 emissions reduce from 400 Mt in 2019 to 27 Mt in 2050, while in the ETO, the emissions in 2050 were 210 Mt. A partial ban of 25% on all new fossil-fuel equipment in buildings is instituted by 2050, while the lifetime of new fossil-fuel equipment is halved (from 15 to 7.5 years) from 2022. These two policy levers contribute to the reduction in emissions by enabling faster phase-out of fossil fuel infrastructure and promoting electrification of buildings.

Manufacturing – In the manufacturing sector, CO_2 emissions reduce from 590 Mt in 2019 to 120 Mt by 2050. Costs of capital of oil and gas equipment in the manufacturing sector increases from 8% in 2022 to 17% while cost of capital of coal equipment increases to 20% by 2050. Investment support of 4% is provided for electric and hydrogen heat production. These measures considerably reduce the attractiveness of fossil-fuel equipment in the PNZ, enabling faster phase-out of fossil fuel technologies.

Energy supply – CO_2 emissions from the power sector are almost eliminated by 2050, with only 14 Mt remaining. All new fossil fuel power capacity additions have reduced lifetimes (from 40 to 25 years), thus enabling faster phase-out of fossil fuel use for power generation. This occurs while the share of electricity in final energy simultaneously grows from 17% in 2019 to 56% in 2050 (Figure 4.26). Similarly, the share of hydrogen grows from insignificant levels to 8% by 2050. New oil and gas capacity additions are banned from 2028 and, grid electricity is subsidized when used for hydrogen production. In addition, capacity investment supports of 10% are provided for dedicated renewables for hydrogen production.

Ambitions for emissions reduction

The Paris Agreement commitments of SEA countries have focused on restricting emissions by 2030 compared to business-as-usual (BAU) projections, but are conditional on international support. The region's economic weight is growing and so is its carbon footprint. Net zero targets are mostly under consideration.

The Philippines has a 2030 goal (NDC from 2021) of reducing GHGs by 75% against projected BAU emissions. Thailand is drafting its zero-carbon emissions master plan, to be presented in November (COP26), and its net zero year is proposed to be around 2065 (Bangkok Post, 2021). Indonesia will explore the opportunity to progress towards net zero emissions by 2060 (Government of Indonesia, 2021).

Access to clean energy technologies and finance are key for the region's decarbonization efforts, and to decouple annual economic growth from carbon-intensive energy growth. The ASEAN energy cooperation is central in directing decarbonization efforts in the region. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

OECD PACIFIC (OPA)

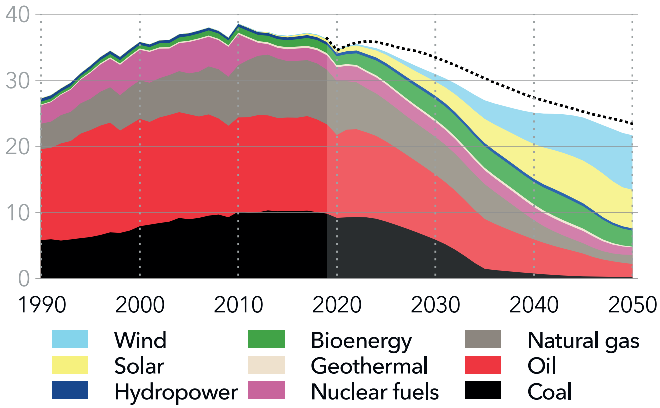
Region statistics		**Population**	**GDP***	**Energy use**	**Net CO_2 Emissions**
2019	Overall	207 m	8.5 trn	36 EJ	2.4 Gt
	Per capita		41 200	175 GJ	11.5 t
2050	Overall	194 m	11 trn	22 EJ	-0.1 Gt
	Per capita		57 200	112 GJ	-0.4 t

*All GDP figures in the report are based on 2011 purchasing power parity and in 2017 international USD

FIGURE 4.28

OECD Pacific primary energy supply by source

Units: EJ/yr



Dotted line: ETO forecast - Historical data source: IEA WEB (2020)

FIGURE 4.29

OECD Pacific share of electricity and hydrogen

Units: Percentages

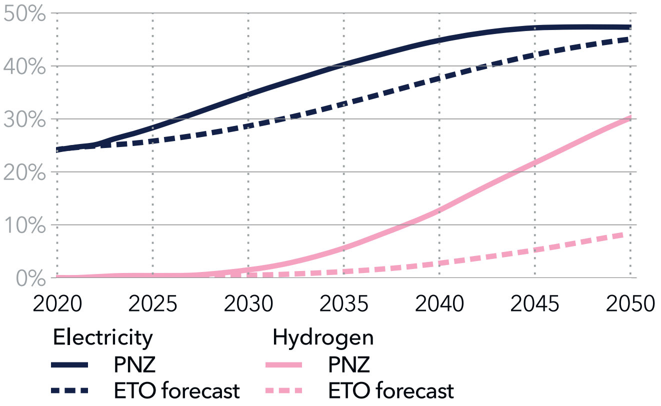
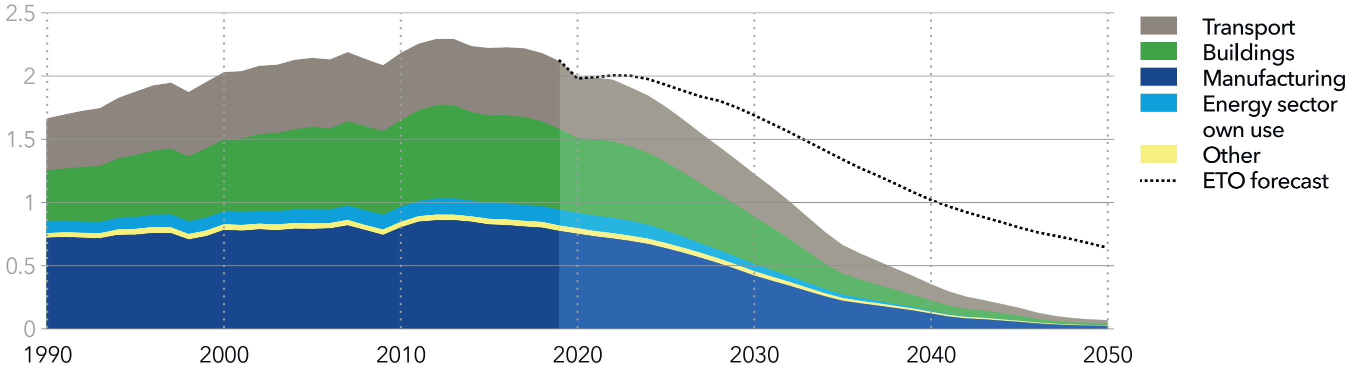


FIGURE 4.30

OECD Pacific energy-related CO_2 emissions by sector

Units: $GtCO_2/yr$



Net zero pathway

OPA's CO_2 emissions reduces from 2.4 Gt in 2019 to -0.1 Gt in 2050 (Figure 4.30); this is achieved by electrification, transitioning to hydrogen and CCS and DAC. Despite the slightly negative emissions, OPA has considerable oil (9%) and natural gas (6%) remaining in the energy mix (Figure 4.28), mostly used in the non-energy sector. Nevertheless, about 65% of the primary energy is obtained from solar and wind in 2050.

Policy levers

Economy-wide economic signals – The rise in average region carbon prices, to USD 100/tCO_2 in 2030 and USD 250/tCO_2 in 2050, is reflected as costs for fossil fuels.

Transport – CO_2 emissions reduce from 540 Mt in 2019 to 25 Mt by 2050. OPA institutes a ban on the sale of passenger ICE vehicles from 2036 and of commercial ICE vehicles from 2035, while subsidizing the transport electricity price by 25% from 2022.

Buildings – CO_2 emissions fall from 640 Mt in 2019 to 16 Mt by 2050. A partial ban of 50% on all new fossil fuel equipment in buildings is instituted by 2050, while the lifetime of new fossil-fuel equipment is halved (from 15 to 7.5 years) from 2022. Additionally, all subsidies on natural gas consumption are eliminated from 2022. These policies contribute towards the reduction in emissions by enabling faster phase-out of fossil-fuel infrastructure and promoting electrification of buildings.

Manufacturing – CO_2 emissions reduce from 780 Mt in 2019 to 25 Mt in 2050. Cost of capital of oil and natural gas equipment in the manufacturing sector increases from 8% in 2022 to 17% in 2050 while cost of capital of coal equipment increases to 20%. An investment subsidy of 10% is given to electric and hydrogen heat production. These considerably reduce the attractiveness of fossil-fuel equipment in the PNZ, which enables faster phaseout of fossil-fuel technologies.

Energy supply – CO_2 emissions from the power sector reduce from 1 Gt in 2019 to 26 Mt in 2050. All new fossil fuel power capacity additions have reduced lifetimes (from 40 to 25 years), thus enabling faster phase-out of fossil fuel use for power generation. Simultaneously the share of electricity in final energy grows, rising from 23% in 2019 to 47% in 2050. Similarly, the share of hydrogen grows from very low levels in 2019 to 30% by 2050 (Figure 4.29). New oil and gas capacity additions are banned from 2024 and grid electricity is subsidized when used for hydrogen production. In addition, capacity investment support of 25% for dedicated renewables for hydrogen production are implemented.

Ambitions for emissions reduction

Among Asian economies, Japan and South Korea followed China in pledging carbon neutrality by 2050 (October 2020). New Zealand targets net zero emissions for non-agricultural activities, set in law in 2019, but Australia lacks clear policies towards achieving Paris Agreement goals, and as such is an outlier among developed countries.

New Zealand's 2050 Emission Reduction Plan, advised by an independent Climate Change Commission, is imminent (December 2021). Japan enshrined carbon neutrality into law (May 2021) and has launched its Green Growth Strategy with sectoral actions plans and envisioned policy tools (METI, 2021). South Korea's 2050 Carbon Neutral Strategy (Government of the Republic of Korea, 2020) outlines a comprehensive energy-decarbonization strategy.

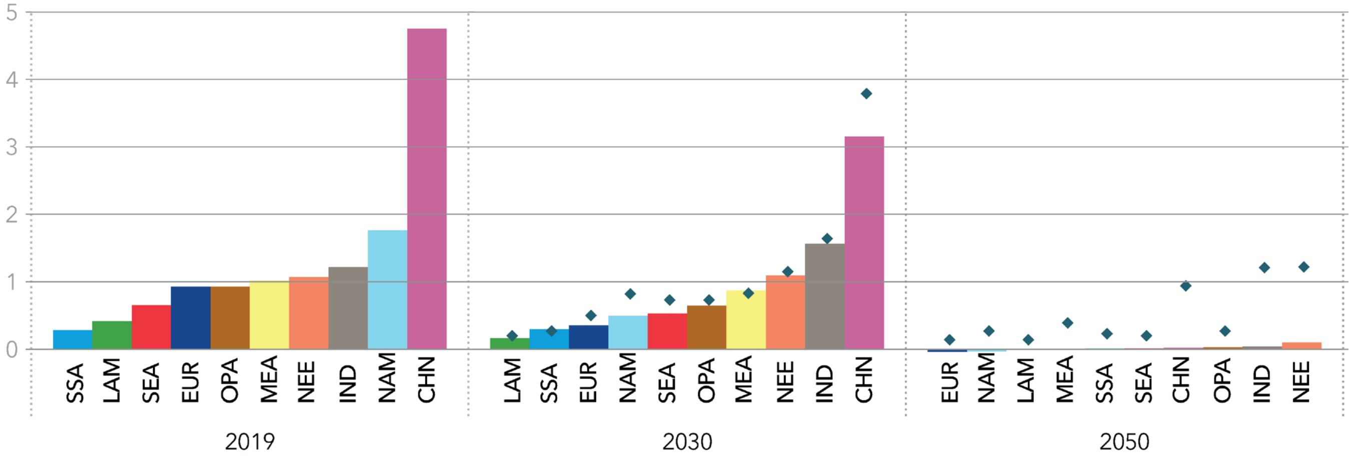
In addition to domestic efforts, Japan and South Korea drive cooperative efforts, e.g., Asia Energy Transition Initiative (AETI) and the Global Green Growth Institute. Both Japan and South Korea have vowed to end financing of overseas coal projects. For more details on the current situation and energy-transition context, please refer to DNV's *Energy Transition Outlook 2021*.

COMPARISON OF THE REGIONS

FIGURE 4.31

Power sector emissions

Units: $GtCO_2$/yr



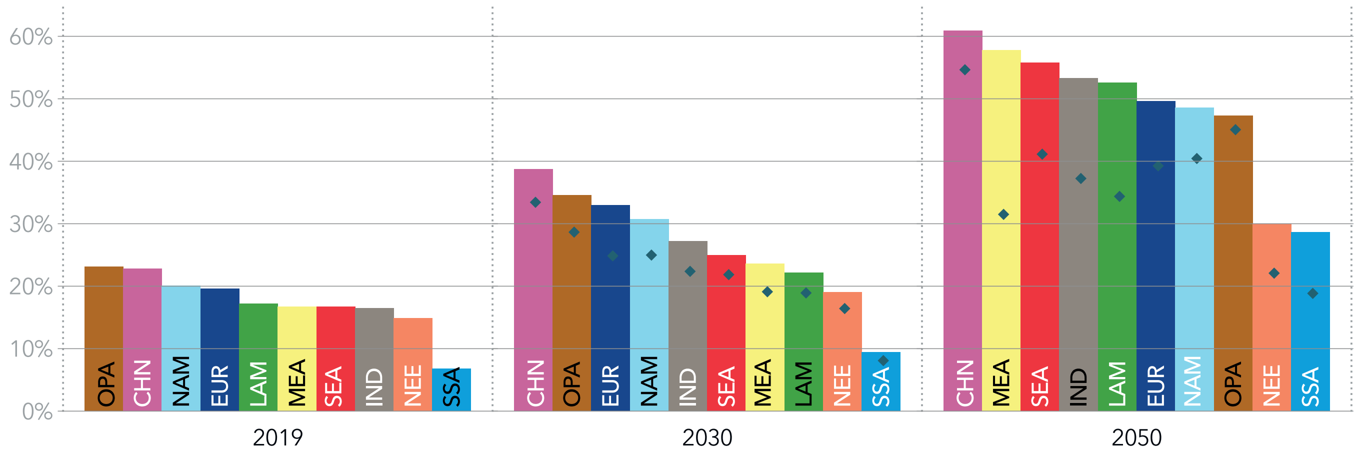
Diamonds represent the results from the ETO forecast

Power sector emissions are measured as CO_2 emissions from power sectors after CCS. These emissions are decreasing everywhere with Europe and North America achieving negative emissions due to their use of biomass. Most regions have negligible emissions in 2050, but 2030 does not see a significant reduction when compared with our ETO. As with 2019, Greater China has the highest power sector emissions in 2030. In contrast, North East Eurasia will have the highest power sector emissions, with Greater China seeing a drastic reduction from 2030 to 2050.

FIGURE 4.32

Share of electricity in final energy demand

Units: Percentages



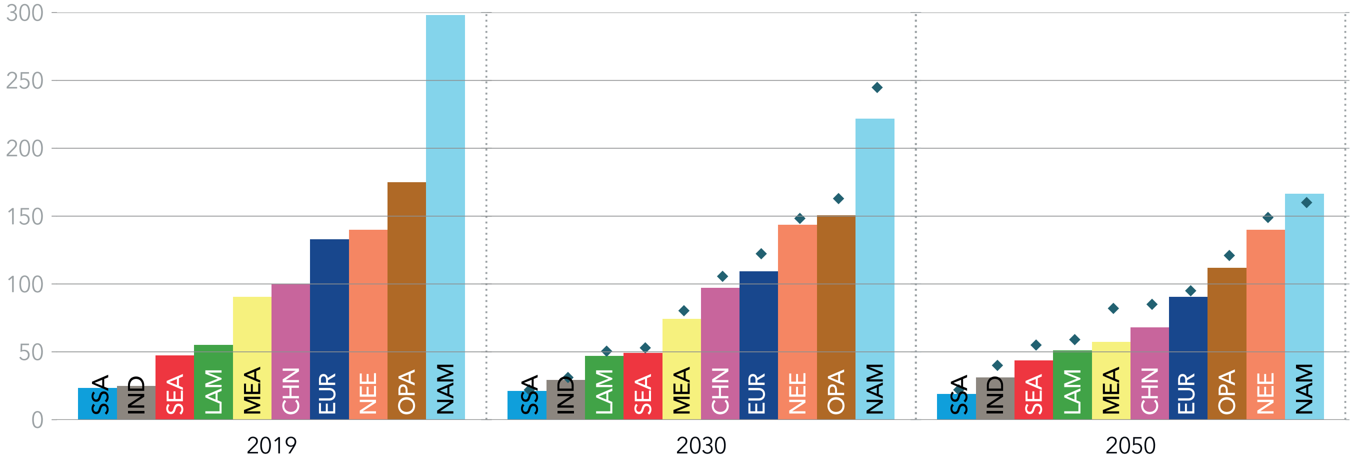
Diamonds represent the results from the ETO forecast

Electrification is measured as share of electricity in final energy demand. This increases substantially in all regions over time and to higher levels than forecast in our ETO. Electrification is pivotal in achieving decarbonization, especially given the role variable renewable energy sources (VRES) have in greening the power sector. Greater China is leading the way in electrification, overtaking OECD Pacific by 2030. Sub-Saharan Africa has larger electrification in 2050 in our PNZ, when compared with the ETO.

FIGURE 4.33

Primary energy demand per capita

Units: GJ/capita



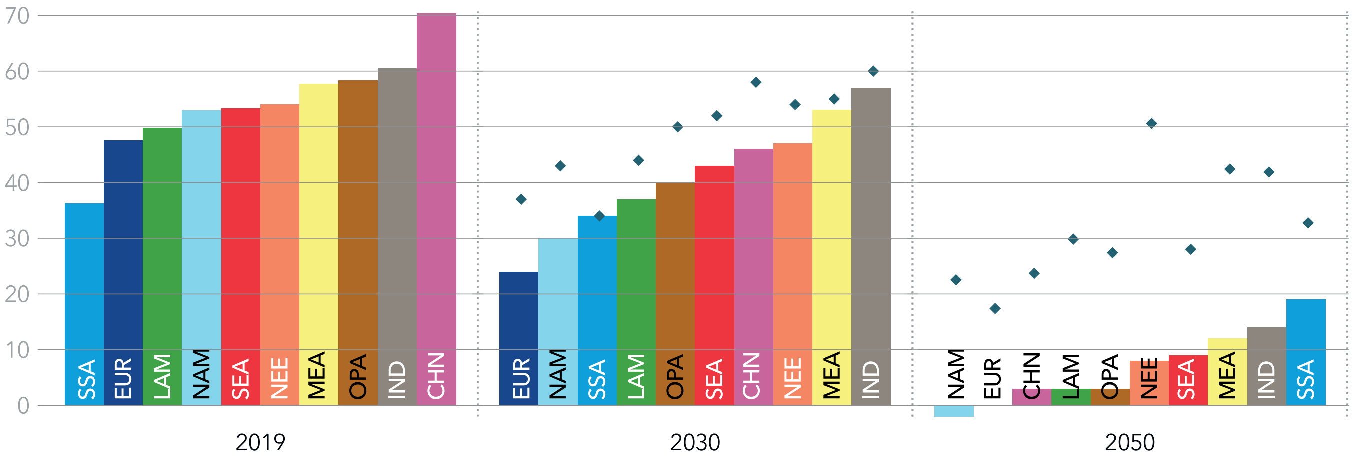
Diamonds represent the results from the ETO forecast

Energy use per capita is measured as gigajoule of primary energy demand per person in a region. All regions except North America see a reduction in energy use per capita in 2050, when compared with the ETO. Given the existing low energy use per capita in Sub-Saharan Africa and Indian Subcontinent, the levels do not undergo drastic reductions from 2019 to 2050.

FIGURE 4.34

Carbon intensity of primary energy consumption

Units: gCO_2/MJ



Diamonds represent the results from the ETO forecast

Carbon intensity of primary energy is measured as the grammes of energy-related CO_2 emissions after CCS, per megajoule of primary energy consumption in the corresponding region. All regions see rapid decarbonization. Surprisingly, North America has the lowest carbon intensity in 2050, and a considerable reduction when compared with our ETO. Middle East and North Africa and the Indian Subcontinent see the largest reductions from 2030 to 2050.

5 METHANE, LAND USE, AND BOLD ACTION

5.1 METHANE

Given the potency of methane (CH_4) as a GHG, it is necessary to apply measures to diminish easy-to-abate CH_4. The concentration of CH_4 in the atmosphere has more than doubled since pre-industrial times and has been second only to CO_2 in driving climate change. Furthermore, approximately half of CH_4 emissions are anthropogenic. Most of these emissions are associated with the agricultural sector (40%), and approximately 35% are from extraction and use of fossil fuels (oil, natural gas, and coal) (UNEP, 2021).

Methane has a shorter half-life (12.4 years) than CO_2, but over both the 100-year and 20-year Global Warming Potential (GWP) time horizon, it is 29.8 and 82.5 times more potent than CO_2 per tonne of GHG emitted, respectively (IPCC, 2021b). For example, the total CH_4 emissions from fossil fuels in 2018 was 113.3 Mt, but this is equivalent to 3.4 $GtCO_2$ when converted to a 100-year GWP, or approximately 11% of the total CO_2 emissions from the energy sector. Using the 20-year GWP, this rises to 9.4 $GtCO_2eq$, or about a quarter of the energy sector's CO_2 emissions. Abating CH_4 emissions from the energy sector is a 'low-hanging fruit' mitigation strategy for a PNZ (IPCC, 2021a). Methane emissions from fossil-fuel extraction and use are well understood and their abatement is so straightforward that the IEA argues that most sectors can be abated by more than half in less than two years. Indeed, many sectors could achieve up to 90% abatement in that short timeframe (IEA, 2021a).

The CH_4 abatement measures in the oil and gas sector include upstream and downstream leak detection and repair, blowdown capture and use of recovered gas with vapour recovery units, replacing pressurized gas pumps and controllers with electric or air systems, and finally capping unused oil and gas wells, among others. The CH_4 abatement measures in coal mining include pre-mining degasification, air methane oxidation with improved ventilation and flooding abandoned mines (IEA, 2021a).

FIGURE 5.1

World CH_4 emissions by fossil fuel

Units: $GtCO_2e/yr$

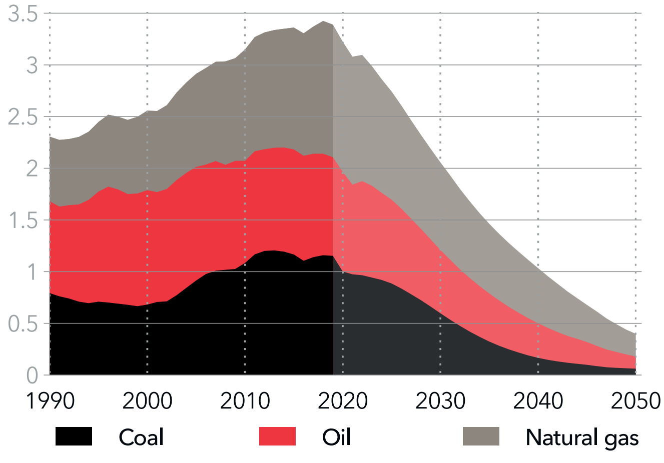
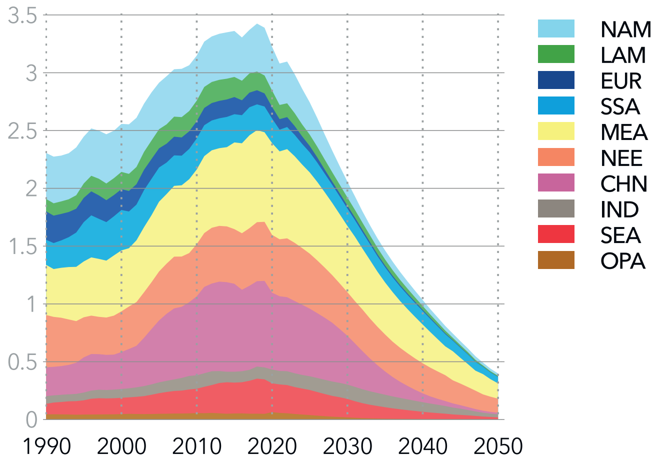


FIGURE 5.2

World CH_4 emissions by region

Units: $GtCO_2e/yr$



Historical data source: EDGAR (2021)

Historical data on CH_4 emissions from all fossil fuels are obtained from Emissions Database for Global Atmospheric Research (EDGAR) (EC-JRC and PBL, 2021). Our abatement assumptions for coal are based on expert opinion, and abatement assumptions for oil and natural gas are based on IEA (2021a).

Methane reductions in our PNZ

Figure 5.1 shows the global CH_4 emissions in the fossil-fuel sector, given in 100-year GWP terms, which rapidly reduce in the PNZ, falling by 88% from 2019 to 2050. The reduction in absolute terms is 3 $GtCO_2eq$. The biggest reduction in CH_4 emissions occurs from coal, mostly because of the stronger decline in coal use in our PNZ. In contrast, the weak reduction in CH_4 emissions from natural gas is due to the persistence of natural gas in the energy system, even in the PNZ. Furthermore, the CH_4 emission intensity of natural gas production and use is higher than that of coal.

Figure 5.2 gives the regional breakdown of CH_4 emissions. Unsurprisingly, MEA and NEE, which have abundant fossil fuels and lower carbon prices, dominate CH_4 emissions, also in our PNZ. Banning new capacity additions for oil and natural gas drastically decreases the CH_4 emissions associated with these fuels.

Figure 5.3 shows the methane emissions in CO_2eq terms, relative to energy-sector emissions, using the 100-year and 20-year GWP. Whereas the 100-year GWP shows that the share of CH_4 emissions increases from 9% today to 17% in 2050, the latter 20-year GWP shows an increase from 25% to 47% of energy-related CO_2 emissions. Despite reductions in CH_4 emissions in absolute numbers, their share in energy-sector GHG emissions increases as natural gas persists, even in the PNZ, mostly coupled with CCS.

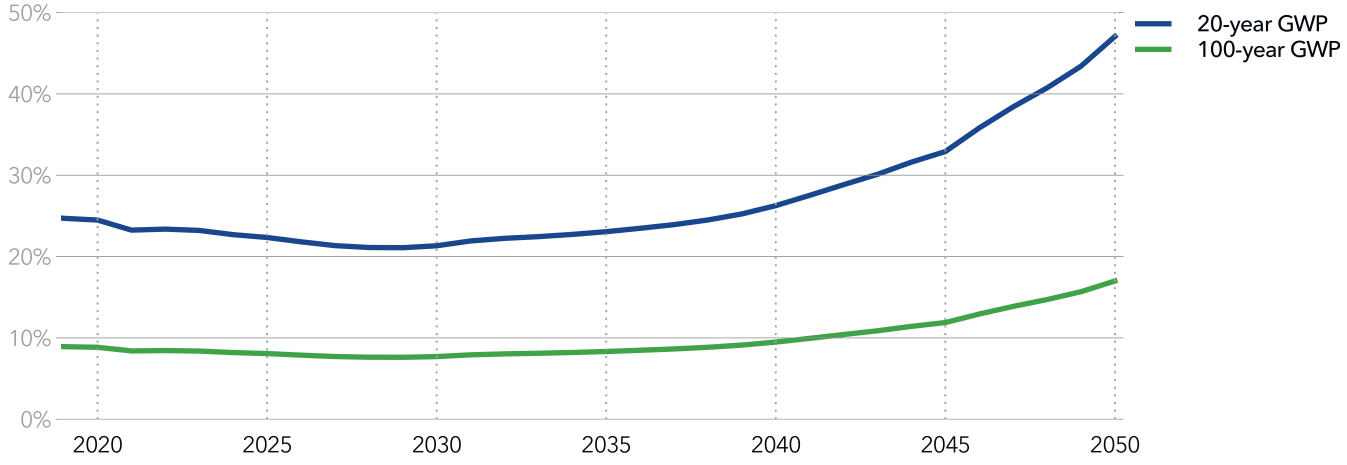
Why only CO_2 and CH_4?

Other greenhouse gases, such as NO_X, HFCs, and CFCs, are more potent climate gases (measured in GWP per tonne of gas emitted) and more persistent than both CO_2 and CH_4. However, we do not consider these in our report. There are two main reasons for this. Firstly, the energy sector is not a significant contributor to these emissions. Secondly, the quantities of these greenhouse gases are low, despite their high potency.

FIGURE 5.3

Methane fraction of energy-related CO_2 emissions

Units: Percentages



5.2 EMISSIONS FROM LAND USE (AFOLU)

Agriculture, forestry, and other land use (AFOLU) is the largest source of GHG emissions outside the energy sector and contributes 23% of global GHG emissions. Land use is both a source and a sink of GHGs and plays a significant role in the cycle of energy, water, and aerosol exchange between land surfaces and the atmosphere. This exchange results in both emissions to and removals of CO_2, CH_4, and N_2O from the atmosphere (IPCC 2019). In this report, as described in 'The Scientific Basis' (Chapter 1), we focus on activities to reach net zero CO_2 emissions and use IPCC low-emission pathways for other GHG emissions. The total net CO_2 emissions to the atmosphere from AFOLU were 6.6 $GtCO_2$ in 2019 and are a net result of deforestation, afforestation, logging and forest degradation, and regrowth of forests following wood harvest or abandonment of agriculture. CO_2 emissions from peat burning and drainage, as well as forest fires, are also included in this figure (GCP, 2020).

In order to achieve a CO_2 net zero pathway from both the energy system and emissions from land use, land use emissions need to fall below zero by 2050. This is because land areas need to act as sinks and compensate for the remaining CO_2 emissions from the energy system. The cumulative CO_2 emissions from energy, processes, and land use overshoots the 1.5°C carbon budget by 230 $GtCO_2$ by 2050. Therefore, land use, as well as other negative emissions technologies (e.g., direct air capture),

Worker on a tree nursery

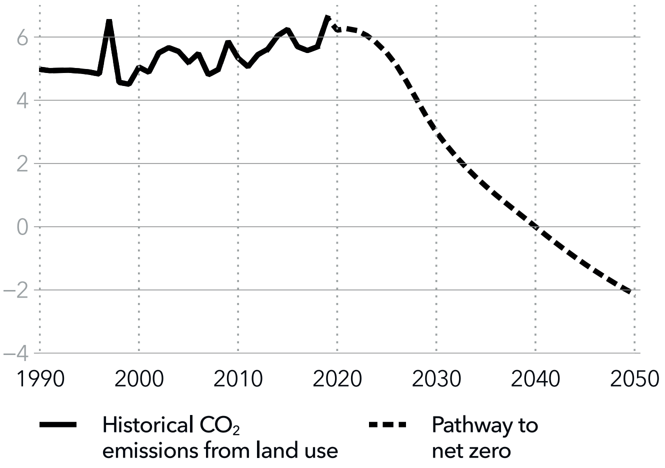
must contribute well beyond 2050 and continue to remove CO_2 from the atmosphere to ensure stabilization at 1.5°C. By 2050, the remaining annual emissions from energy and industrial processes after DAC are 2.1 $GtCO_2$; this means that land-use emissions must decrease from today's level, reach negative -2.1 $GtCO_2$ in 2050, and then, together with other CO_2 reduction measures, continue to remove CO_2 emissions for the remaining part of the century. Assuming a continued scaling up of DAC, as well as further improvements in land use after 2050, this could result in total negative emissions of -5 $GtCO_2$/yr from 2070, and then continue towards 2100. Cumulatively, this amounts to -230 $GtCO_2$, which would eliminate the 1.5°C carbon overshoot by 2100.

Figure 5.4 shows a pathway for CO_2 land-use emissions through to 2050. Similar to our approach in the energy system, we think it is feasible for emissions from land use to decrease slowly initially, and then for the pace of reduction to accelerate. First, the trend of increasing emissions must be reversed, then, by 2030, a rapid decline is necessary such that CO_2 emissions from land use reach net zero by 2040. Thereafter, land use achieves negative emissions such that by 2050 negative emissions of 2.1 $GtCO_2$ compensate for remaining emissions from the energy system, thereby achieving an overall net zero result.

FIGURE 5.4

Land use CO_2 emissions for a pathway to net zero

Units: $GtCO_2$/yr



Agriculture, forestry, and other land use (AFOLU) is the largest source of GHG emissions outside the energy sector.

Decarbonization from land use vs the energy system

Is this development in land use plausible? Why not remove emissions from the energy system instead? We believe that changes in land use are comparatively easier than full decarbonization of some of the hard-to-abate sectors, such as aviation, or for developing regions to reach net zero by 2050. Our view is consistent with many scientific reports on nature-based solutions as well as with conclusions reached by the IPCC. Among the 90 global emission pathways included in the IPCC's 1.5°C report (2018), the range of removals of CO_2 emissions in 2050 varies between -1 to -11 $GtCO_2$/yr. Houghton et al. (2015) estimated that the re-establishment of forests on about 500 Mha of land that were previously forested, but not currently used productively, would remove 3.7 $GtCO_2$/yr for decades; this area is equivalent to 10% of the world's available agricultural land. Soil carbon sequestration and restoration of degraded land have co-benefits for agriculture and have the potential to reduce emissions by 2.3-5.3 $GtCO_2$/yr (IPCC, 2018).

In order to achieve our proposed level of negative emissions from changes in land use, the model includes, but is not restricted to, afforestation and reforestation. Equally important are measures to reduce emissions through significantly limiting deforestation and forest degradation, as well as preservation of land and carbon stocks. There is considerable uncertainty about the effect of policies and incentives to limit emissions from land use. In contrast to emissions from energy-related activities, these emissions are a direct response to population growth and the associated requirement for increased food production. However, it will not be possible to limit global warming to 1.5°C without addressing emissions from land use. Therefore, GHG emissions, particularly CO_2 from land use, must decline and become negative in order for global warming to stabilize at 1.5°C.

5.3 OUTSIDE THE ENERGY SYSTEM

Among GHG emissions caused by human activity, 72% stem from the energy system (WRI, 2021). For the 28% of emissions that do not originate from the energy system, 23% comes from AFOLU and most of the rest from waste and chemicals.

The energy system is the main focus of this pathway report, and, as explained in the previous section, we have also detailed CO_2 emissions from the AFOLU sector in order to obtain a more-complete net zero scenario, including all major CO_2 emissions.

What happens with emissions outside the energy system is also of considerable importance for future global warming, both in the short term and the long term. For instance, the recent IPCC report (IPCC, 2021a) highlighted that curbing methane emissions from all sources (energy, as well as other sectors) has the best potential for requiring the least amount of effort to limit global temperature rise in the next few decades.

Emissions outside the energy system are indirectly accounted for in our PNZ, as described in the section 'The Scientific Basis' at the start of the report. It is well established that representative pathways to 1.5°C are close to net zero CO_2 emissions in 2050.

The scientific agreement that net zero CO_2 emissions in 2050 would indicate a warming of 1.5°C is dependent on the development of non-CO_2 GHGs following representative pathways similar to reductions in the energy system.

The total sum of GHGs ultimately determines the global average temperature increase, and the logical implications are clear:

- A more aggressive reduction of GHG in other sectors, provides slightly more leeway in the energy sector, and still enables reaching 1.5°C.
- With less action on reducing emissions in the other sectors, in order to reach 1.5°C it will be necessary to cut emissions even faster and more severely in the energy sector.

It is beyond the scope of this report to describe how CH_4 and N_2O agricultural emissions or emissions from waste and landfill 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.

It is, however, clear that reaching 1.5°C is extremely difficult, and to reach this goal all sectors – both within and outside the energy system – need to act together and with urgency.

> Curbing methane emissions from all sources (energy, as well as other sectors) has the best potential for requiring the least amount of effort to limit global temperature rise in the next few decades.

5.4 THIS PATHWAY NEEDS BOLD ACTION – NOW

The pathway to net zero emissions starts today. It is already three years since the IPCC special report on 1.5°C illustrated their 90 alternative scenarios to reach 1.5°C; all four illustrative pathways, and almost all others, had steep reductions in emissions starting at around 2020. The lack of urgent climate actions between 2018 and 2021 means that the prospect of reaching net zero is even more challenging. Ironically, the COVID-19 pandemic resulted in significant reductions in emissions, but these are of little long-term help as emissions are now rising steeply again.

We have lost these three years, and there is no room for any further delays. As stated in IEA's 1.5°C report in May this year (IEA, 2021c): "Action this year and every year after" is essential.

In the DNV Pathway to net zero (PNZ), the reduction in emissions starts now, and 2022 emissions are down from this year. In spite of the built-in inertia in the fossil-fuel system, reductions in fossil-fuel use – in particular coal – will start now. This is by no means easy, but easy pathways to net zero and 1.5°C do not exist.

How realistic is our PNZ? It is definitively not the most likely future in the sense that it requires very bold, coordinated, and proximate action from governments around the world and there is currently no clear indication that such actions will indeed be taken. Our ETO is our best attempt to forecast the trajectory that we are on – with the economic, technological, and political developments that we expect, with reasonable certainty, to unfold. The PNZ energy transition is dramatically faster and much more demanding.

It is challenging from many perspectives. Conflicting priorities and a range of barriers – as listed in our ETO – stand in the way of urgent policy action. Resource limitations and ramp-up challenges threaten to jeopardize the rapid scale-up needed in new technologies. A dramatic turnaround in the financing sector is essential to fund the transition.

That does not mean the PNZ cannot be achieved. It is based on technologies that already exist, and a scale-up of these. Resource limitations will influence the transition but are not likely to be a roadblock; for example, there is more than one battery chemistry that can be used in EV batteries. As we have pointed out in the expenditure section in Chapter 2, the additional costs required for achieving the PNZ are less than 1% of GDP, and even with this additional cost added, the PNZ places us on track to spend a lower share of our GDP on energy in the future than we do today. And, finally, the pandemic has proven that immediate and tough political actions can be taken should the problem be perceived as sufficiently urgent and critical.

The window is closing to reach 1.5°C – but the PNZ is both technically and politically feasible – and therefore its achievement is a realistic possibility if we can harness the best of our efforts.

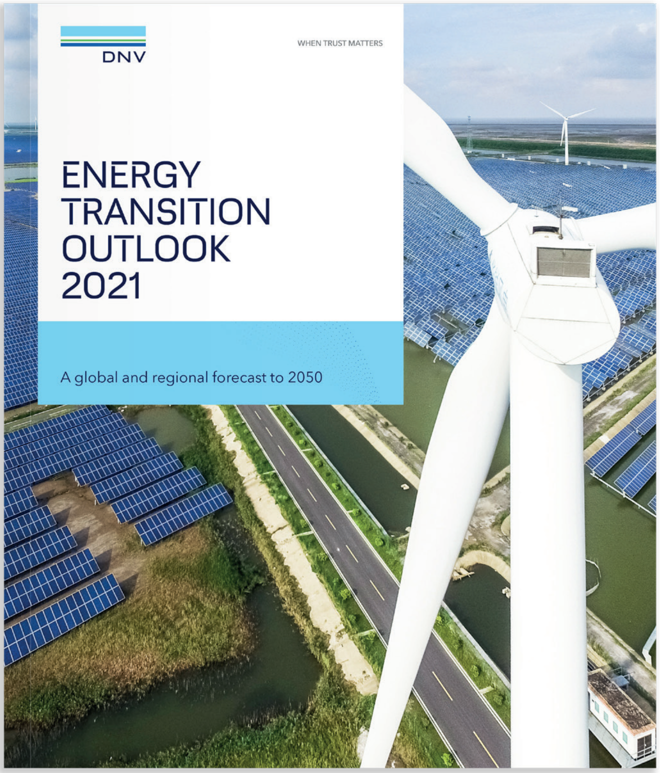
The most critical constraint is clearly time. Coordinated efforts across all regions and all sectors are needed – in developed and developing nations, and in harder and easier sectors alike. As the sectoral and regional roadmaps in this report clearly show, this does not mean everyone must do the same thing at the same time – but everyone must act.

We strongly caution that the PNZ will be out of reach if the world waits another five years before taking the important first steps. 2022 is almost upon us, and policy and decision makers around the world must change direction and introduce the necessary measures as soon as possible, as outlined in the roadmaps in this report.

> The window is closing to reach 1.5°C – but the PNZ is both technically and politically feasible.

The timing of this report is not arbitrary. One week after publication, COP26 will commence in Glasgow after a one-year delay due to the pandemic. We hope that this report – together with other landmark reports from the IPCC, IEA, and other organisations – will spark urgent action. As highlighted at the start of this publication, for the world to reach the net zero emissions required for a 1.5°C future, leading regions and sectors must go much further, much faster. We hope that decision makers will be persuaded that they cannot rest on the laurels of their net zero ambitions, and that they need to do much more than that. And, above all, we emphasize the urgency of acting now.

ENERGY TRANSITION OUTLOOK 2021 REPORTS OVERVIEW



Energy transition outlook

Our main publication details our model-based forecast of the world's energy system through to 2050. It gives our independent view of the most likely trajectory of the coming energy transition, and covers:

- **The global energy demand** for transport, buildings, and manufacturing
- **The changing energy supply mix**, energy efficiency, and expenditures
- **Detailed energy outlooks** for 10 world regions
- **The climate implications** of our forecast.

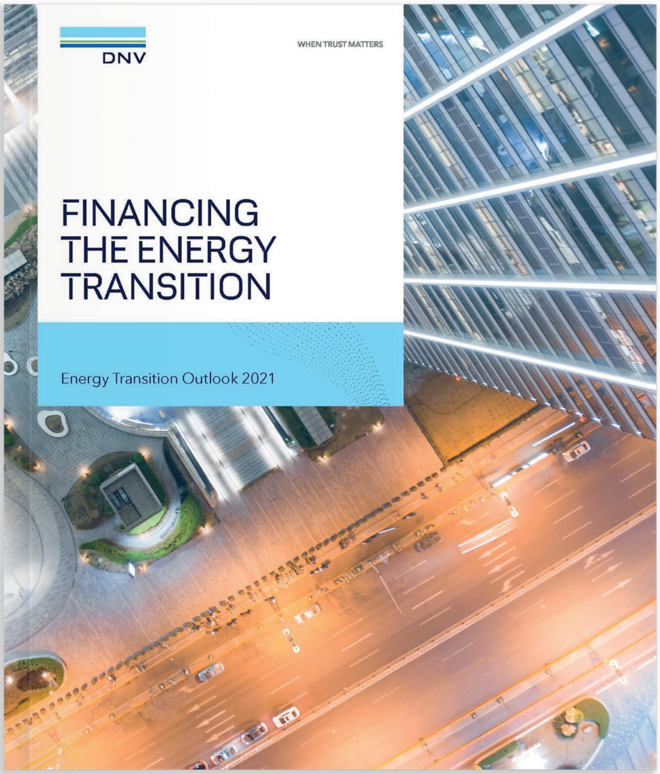
We also provide details on our model and main assumptions (i.e., population, GDP, technology costs and government policy). Our 2021 Outlook explores, inter alia, the impact of COVID-19 and the growing importance of hydrogen as an energy carrier.

Technology progress report

We explore how key energy transition technologies will develop, compete, and interact in the coming 5 years. The ten technologies are:

- **Energy production**: floating wind, solar PV, and waste to fuel and feedstock
- **Energy transport, storage, and distribution**: pipelines for low-carbon gas; meshed HVDC grids, new battery technology
- **Energy conversion and use**: novel shipping technologies, EVs and grid integration, green hydrogen production, CCS.

We attempt to strike a balance between technical details and issues of safety, efficiency, cost, and competitiveness. The interdependencies and linkages between the technologies are a particular area of focus.



Financing the energy transition

Focuses on the financial opportunities and challenges for financiers, policymakers, developers, and energy companies:.

- **An affordable transition** – considering whether a Paris-compliant transition is affordable, and what may be needed to mobilize and redirect capital
- **Accelerating the transition** – examining the role of financial markets, policy, and regulation, and how to get capital to flow to where it can have the most impact on emissions
- **Ensuring a just transition** – exploring the importance of balancing sustainability priorities, ensuring co-benefits, and building climate resilience.

The report combines DNV's independent energy forecast to 2050 with views from a diverse set of leaders in the energy and finance sectors.

Maritime forecast

The Maritime Forecast to 2050 offers shipowners practical advice and solutions as shipping's carbon reduction trajectories rapidly head towards zero.

- **DNV's new carbon risk framework** allows detailed assessments of fuel flexibility and Fuel Ready solutions, the economic robustness of fuel and energy efficiency strategies, and their impact on vessel design.
- **Decarbonization** is leading to increased regulatory requirements, new cargo-owner and consumer expectations, and more rigorous demands from investors and institutions.
- **Investments in energy and fuel production** will be essential to shipping's efforts to decarbonize.

This is the grand challenge for the maritime industry. But by working together as an industry, embracing fuel flexibility, and consulting with expert partners, shipping can reach its destination.

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THE PROJECT TEAM

This report has been prepared by DNV as a cross-disciplinary exercise between the DNV Group and two of our business areas – Energy Systems and Maritime – across 15 countries. The core model development and research has been conducted by a dedicated team in our Energy Transition research programme, part of the Group Development and Research unit, based in Oslo, Norway. In addition, we have been greatly assisted by the external Energy Transition Outlook Collaboration Network.

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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 2020, 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 2018) numerical data is mainly based on IEA data from World Energy Balances © OECD/ IEA 2020, www.iea.org/ statistics, License: www.iea. org/t&c; as modified by DNV

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DNV is an independent assurance and risk management provider, operating in more than 100 countries, with the purpose of safeguarding life, property, and the environment. Whether assessing a new ship design, qualifying technology for a floating wind farm, analysing sensor data from a gas pipeline or certifying a food company's supply chain, DNV enables its customers and their stakeholders to manage technological and regulatory complexity with confidence. As a trusted voice for many of the world's most successful organizations, we use our broad experience and deep expertise to advance safety and sustainable performance, set industry standards, and inspire and invent solutions.

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