DNV

WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK 2022 EXECUTIVE SUMMARY

A global and regional forecast to 2050

FOREWORD

Looking beyond today's high energy prices to see what the longer-term energy future holds is difficult. That is what this Outlook does. Our forecast considers the demand shock of the pandemic and the supply shock that came with Russia's invasion of Ukraine and concludes that those developments exert little long-term influence over a transition that will be rapid and extensive.

The present turbulence in energy markets is not inconsequential, however. Europe will transition to a renewables-dominated power system more rapidly, but higher energy prices may dampen investment in clean energy elsewhere. These two effects tend to offset each other globally over time. Supply chain disruptions will continue in the shorter term, delaying the global EV 'milestone' (when the EV share of new vehicle sales surpasses 50%) by one year in our forecast – to 2033. But here too there are compensatory developments, where high prices will encourage energy-saving behaviour among power consumers. For aviation, we also forecast a permanent reduction of 7% in annual passenger trips due to pandemic-related changes in work habits.

This year, our forecast sees non-fossil energy nudge slightly above 50% of the global energy mix by 2050. The principal underlying dynamic is rapid electrification, with supply climbing from 27 PWh/yr now to 62 PWh/yr in 2050. We detail how this leads to enormous energy-efficiency gains in power generation and end-use.

We are entering a prolonged period where efficiency gains in our energy system outstrip the rate of economic growth. Over the long term this means the world will spend significantly less on energy as a proportion of GDP. In theory, that should provide policymakers with confidence to accelerate the transition.

Bold and brave policy choices are critical in the face of climate change. This year, for the first time, we include our 'Pathway to Net Zero' alongside our 'best estimate' forecast for the energy transition. Put another way, we compare a forecast that we think will unfold with a pathway that we hope the world will embrace. Even under a net zero pathway we think it infeasible for the world to completely discontinue fossil-fuel use, which is why you will find a 13% fossil share in the energy mix in our Pathway to Net Zero in 2050. That overshoot in fossil use will require huge expenditure on carbon capture and removal efforts in the 2040s – running to USD 1 trillion per year.

Deglobalization is much talked about. However, the energy transition is likely to see unprecedented regional and cross-industry cooperation – for example within hydrogen ecosystems or the creation of green shipping corridors. DNV will, as an independent provider of technical expertise, strive to catalyse such cooperation wherever we can.

I hope you find this Outlook a useful strategy and planning tool, and, as ever, I look forward to your feedback.

Remi Eriksen

Group President and CEO

DNV

HIGHLIGHTS

SHORT TERM

High energy prices and a greater focus on energy security due to the war in Ukraine will not slow the long-term transition

– Europe aims to accelerate its renewables build-out to achieve energy security
– In the rest of the world, tackling high energy and food prices may shift decarbonization down the list of priorities in the short term
– The long-term influence of the war on the pace of the energy transition is low compared with main long-term drivers of change: plunging renewables costs, electrification, and rising carbon prices

COP26 and the IPCC have called for urgent action which has not materialized: emissions remain at record levels

– Emissions must fall by 8% each year to secure net zero by 2050
– Opportunities for intensified action abound – the transition is opening up unprecedented opportunities for new and existing players in the energy space

LONG-TERM FORECAST

Electricity remains the mainstay of the transition; it is growing and greening everywhere

– With an 83% share of the electricity system in 2050, renewables are squeezing the fossil share of the overall energy mix to just below the 50% mark in 2050
– Despite short-term raw material cost challenges, the capacity growth of solar and wind is unstoppable: by 2050 they will have grown 20-fold and 10-fold, respectively

Hydrogen only supplies 5% of global energy demand in 2050, a third of the level needed for net zero

– Pure hydrogen use scales in manufacturing from the early 2030s and in derivative form (ammonia, e-methanol and other e-fuels) in heavy transport from the late 2030s
– Green hydrogen from dedicated renewables and from the grid will become dominant over time; blue hydrogen and blue ammonia retain important roles in the long term

PATHWAY TO NET ZERO

We are heading towards a 2.2°C warming; war-footing policy implementation is needed to secure net zero by 2050

– Massive, early action to curb record emissions is critical; the window to act is closing
– No new oil and gas will be needed after 2024 in high income countries, and after 2028 in middle- and low-income countries.

Net zero means leading regions and sectors have to go much further and faster

– OECD regions must be net zero by 2043 and net negative thereafter; China needs to reduce emissions to net zero by 2050
– Renewable electricity, hydrogen and bioenergy are essential, but insufficient: almost a quarter of net decarbonization relies on carbon capture and removal combined with land-use changes (reduced deforestation).

Highlights – short term

High energy prices and a heightened focus on energy security due to the war in Ukraine will not slow the long-term transition

Europe is likely to accelerate its energy transition during and after the war in Ukraine. There will be a rapid phase-out of imported Russian fossil fuel sources and rising to the top of the agenda will be energy security, which hinges on a renewables-dominated energy system and measures to accelerate energy efficiency. Energy security and sustainability thus pull in the same direction. Affordability is a major short-term concern with record high prices for natural gas and electricity. The policy response focuses on diversification of supply initially, giving some fossil sources a short-term boost, but the main policy thrust is to achieve energy independence for Europe earlier, based primarily on renewable energy.

Outside Europe, and particularly in low- and middle-income countries, high energy and food prices plus the looming risk of global recession have shifted attention to short-term priorities. Long-term climate change investments and actions like electricity infrastructure build-out are likely to be postponed. High-priced LNG could make for a short-term coal resurgence, and although renewables are local and support domestic energy security, domestic coal could find favour over imported gas.

The net effect is that, due to short-term pressure, there is reduced likelihood of extraordinary action being taken to reach a net-zero future; however, the steady pace of the financially-driven energy transition will continue. Short-term commodity cost increases and the war in Ukraine will not put the brakes on the big drivers of the transition like the plunging costs of renewables, electrification, and rising carbon prices.

COP26 and the IPCC have called for urgent action which has not materialized: emissions remain at record levels

At COP26, UN Secretary António Guterres stressed the urgency of immediate action on global warming, calling it a Code Red for humanity. His warning has been amplified by the successive AR6 reports from the IPCC. COP26 saw agreements on important issues like coal phase-down, methane reduction, and land-use changes, but that sense of urgency has generally not been reflected since then in national policy plans or actions.

Global GHG emissions reduction of some 8% every year is needed for a net-zero trajectory. In 2021, emissions were rising steeply, approaching pre-pandemic all-time highs, and 2022 may only show a 1% decline in global emissions. That makes for two 'lost' years in the battle against emissions.

The lack of action is attributed to a weakening global economy amid inflation challenges. However, our analysis points to enormous opportunities inherent in decarbonization for both companies and nations. Renewables expenditures are expected to double over the next 10 years to more than USD 1,400 billion per year, while grid expenditures also are likely to exceed USD 1,000 billion per year in 2030. We show that building out renewable technologies does not come at a green premium, but rather as a green prize. Owing to the considerable efficiencies linked to electrification and the plunging costs of renewables, the world will be spending far less on energy as a proportion of GDP by 2050. There is scope for accelerated action, and for private sector frontrunners to run well ahead of anticipated governmental support.

Highlights – long term

Electricity remains the mainstay of the transition; it is growing and greening everywhere

The strongest engine of the global energy transition is electrification, expanding in all regions and almost all sectors, while the electricity mix itself is greening rapidly. Electricity production will more than double, with the share of electricity rising from 19% to 36% in the global energy mix over the next 30 years. In addition, electricity will take over and dominate hydrogen production.

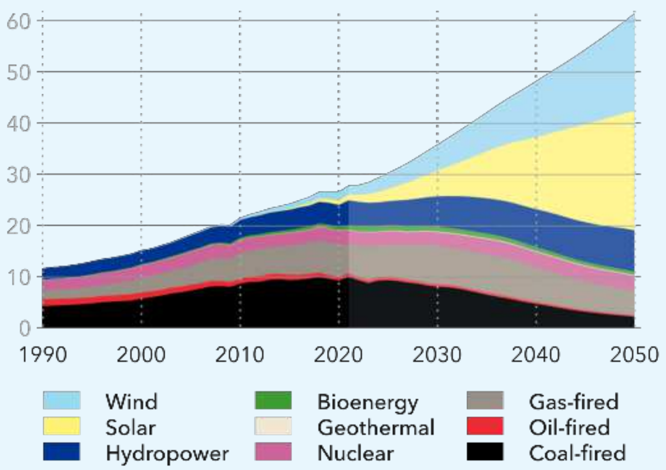
The share of fossil fuels in the electricity mix reduces sharply from the present 59% to only 12% in 2050. Solar PV and wind are already the cheapest forms of new electricity in most places, and by 2050 it will grow 20-fold and 10-fold, respectively. Solar PV takes a 38% share of electricity generated in 2050 and wind 31%.

Nuclear will only manage to slightly increase present production levels due to its high costs and long lead times; its share of the electricity mix will therefore decline. The strong growth of renewables in electricity is the main reason why the fossil-fuel share of total energy use in 2050 is pushed to just below the 50% mark.

FIGURE 1

World grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2022), GlobalData (2022)

Hydrogen will be only 5% of global energy demand in 2050, a third of the level needed for net zero

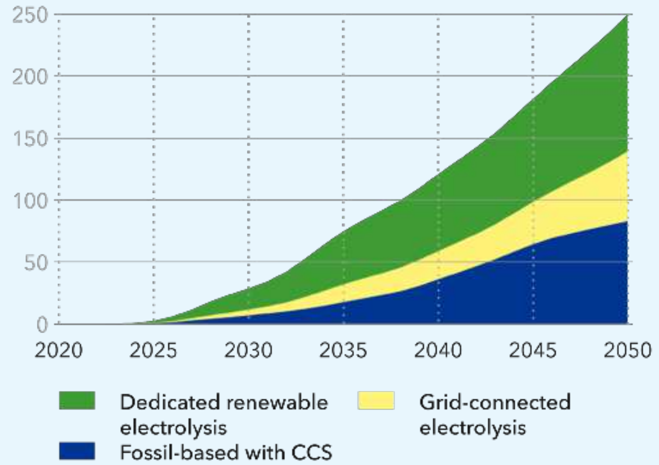
Hydrogen is inefficient and expensive compared with direct electricity use but is essential for decarbonizing hard-to-abate sectors like high-heat processes in manufacturing, and maritime transport and aviation. However, the global uptake of hydrogen as an energy carrier sees it supplying only 5% of energy demand in 2050, a third of the level needed in a net-zero energy mix.

Hydrogen will scale in the manufacturing sector from the early 2030s in the leading regions. In heavy transport like aviation and maritime, we will see the hydrogen derivates ammonia, e-methanol and other e-fuels starting to scale in the late 2030s. We see a more limited uptake of hydrogen in heavy, long-distance trucking, and in the heating of buildings in areas with existing gas distribution networks, but almost zero use in passenger vehicles. Green hydrogen from dedicated renewables and from the grid will dominate hydrogen production; blue hydrogen remains important, for example in ammonia production. The number of hydrogen initiatives in hard-to-abate sectors is growing rapidly, but few have reached final investment decision.

FIGURE 2

World production of hydrogen and its derivatives for energy purposes by production route

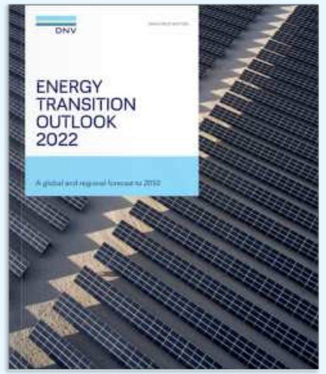
Units: MtH_2/yr

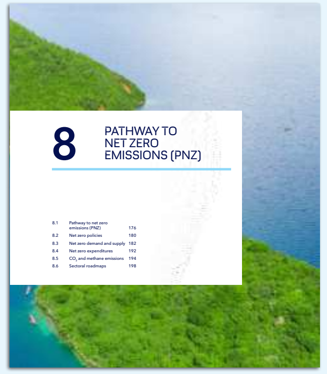


Closing the gap to 1.5°C

In this year's ETO, DNV has added a Pathway to Net Zero scenario that outlines what needs to be done by 2050 for the world to close the gap from the most likely 2.2°C trajectory to the agreed 1.5°C future.

How big is the gap?
Global CO_2 emissions were 38 Gt in 2020 and by 2050 the annual emissions gap is 22 Gt CO_2 with cumulative emissions resulting in about 0.2°C difference.





Between 2050 and 2100, the ETO projection is that net annual emissions reduce slowly from 22 Gt towards 0, while the PNZ has net-negative annual emissions from 2050.

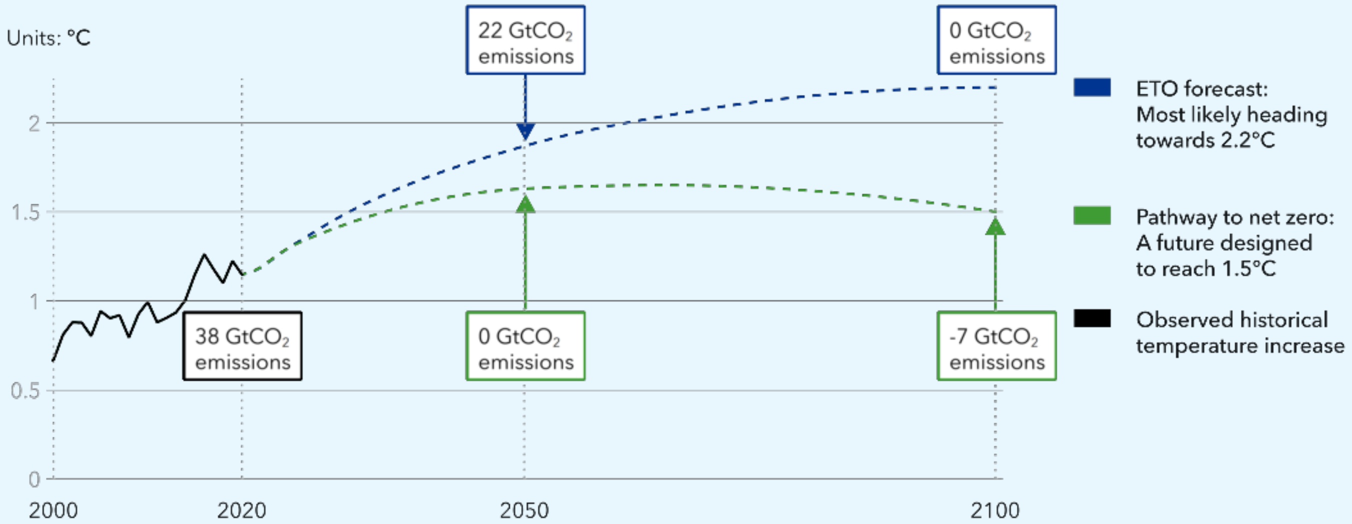
In 2100, the emissions gap is 7 Gt CO_2 of negative emissions, corresponding to around 0.7 °C temperature difference and 1,050 Gt of cumulative CO_2 emissions.

How to close the gap?
The gap must be closed by a combination of:

- **Reduced combustion** of fossil fuels, replacing coal, oil and gas with renewables and nuclear
- **Energy efficiency** improvements
- **Carbon capture and removal**, including net negative emissions from:
  - Bioenergy with CCS
  - Direct air capture
  - Nature-based solutions (e.g. reforestation)

Closing the gap to 1.5°C

Change in global surface temperature relative to 1850-1900



Historical data source: IPCC AR6 WGI (2021)

Highlights – Pathway to Net Zero

We are heading towards 2.2°C warming; war-footing policy implementation is needed to secure net zero by 2050

The Paris Agreement aim of limiting global warming to 1.5°C is still possible, but the window to act is closing. Securing 1.5°C without a temporary carbon overshoot is already out of reach. DNV's ETO forecast of the 'most likely' energy future – one driven by market forces and often dilatory climate policies – results in 2.2°C warming by the end of the century.

On their own, technological and market developments are insufficient drivers of the change needed for net zero; war-footing-like policy implementation with massive early action across regions and sectors is needed. Low-income regions need dedicated technology and financial assistance to transition at the required rate.

No new oil and gas will be needed after 2024 in high-income countries and after 2028 in middle- and low-income countries. However, renewables need to triple and grid investment rise more than 50% over the next 10 years.

Net zero means leading regions and sectors must go below zero before 2050

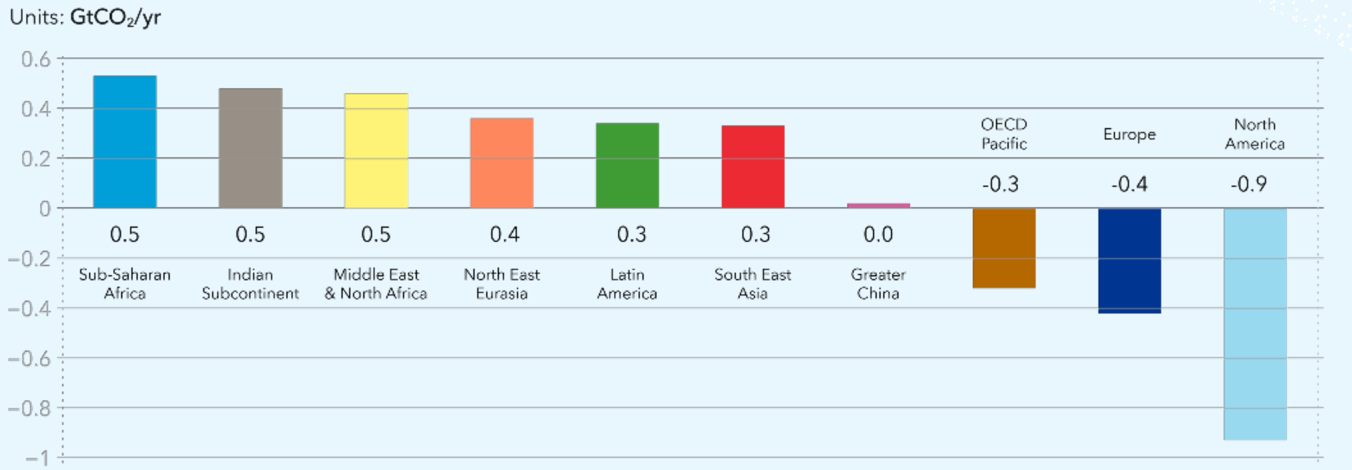
Different regions and sectors have different starting points and capabilities, and if the world is to reach net zero in 2050, leading regions and sectors have to go much further and faster. OECD regions must be net zero by 2043 and net negative thereafter via carbon capture and removal. China needs to reduce emissions to zero by 2050, while the remaining regions all reduce emissions significantly, but do not reach net zero by mid-century.

Some sectors, like power, will reach net zero before 2050, while other sectors, like cement and aviation, will still have remaining emissions. Maritime needs a strengthened IMO strategy to reduce emissions by 95% by 2050.

Renewable electricity, hydrogen and bioenergy are essential, but insufficient: almost a quarter of net decarbonization relies on carbon capture and removal, including CCS from power and industry, direct air capture, and nature-based solutions.

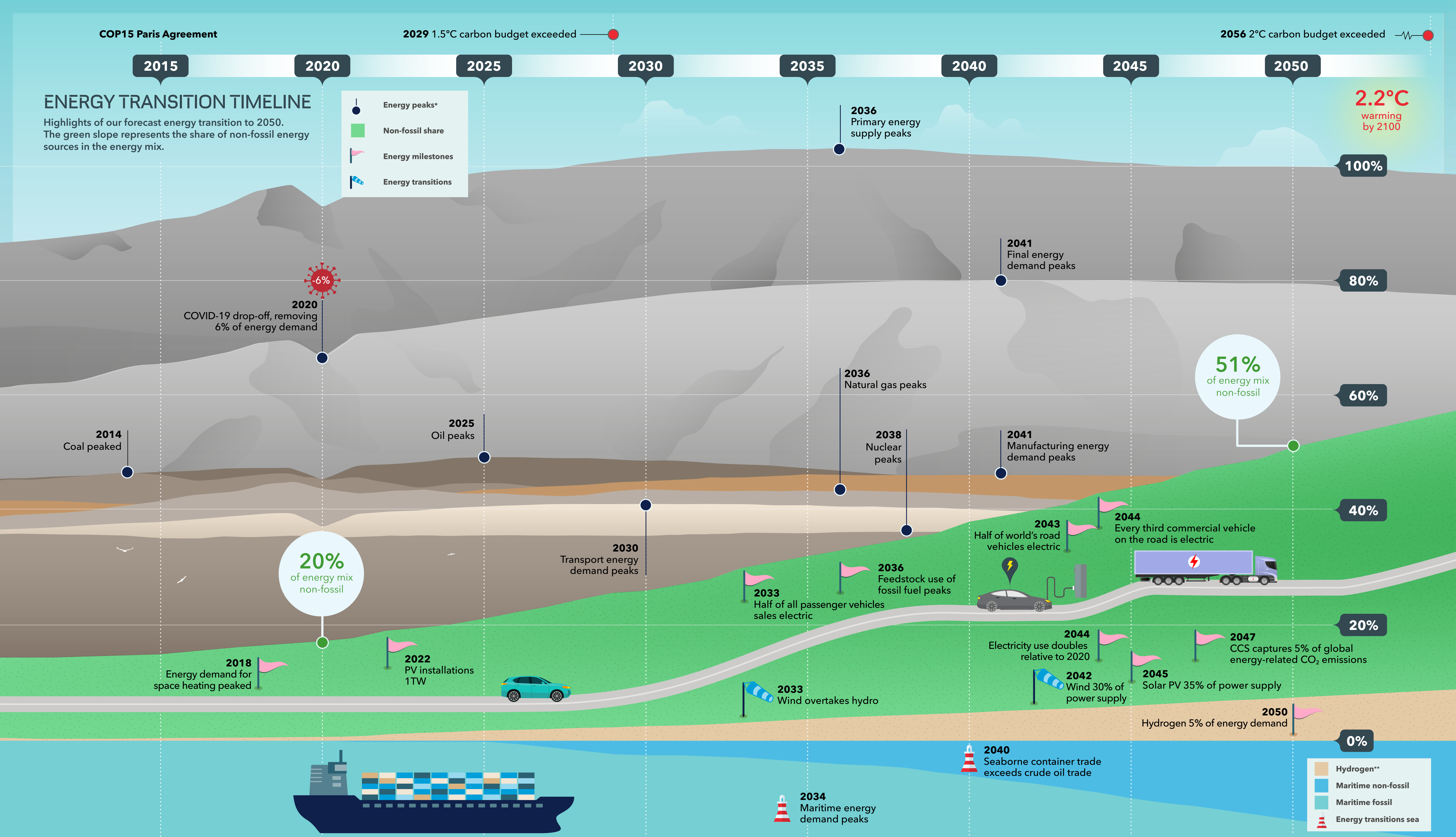
Leading regions have to transition faster and reach net zero earlier

2050 Energy-related CO_2 emissions after CCS and DAC



ENERGY TRANSITION TIMELINE

Highlights of our forecast energy transition to 2050.
The green slope represents the share of non-fossil energy sources in the energy mix.



*Energy peaks not to scale relative to primary energy **Average primary energy used for production of H_2 & derivatives.

ENERGY DEMAND

Buildings
Global energy demand up 24% by 2050, from 120 EJ/yr in 2020 to 148 EJ/yr in 2050.

Floor space grows much faster than overall buildings energy demand (+52% residential and a doubling of commercial space), implying important efficiency gains.

Electricity takes an increasingly larger share in the buildings energy mix (32.5% in 2020 to 55.5% in 2050), but will be used with increasing efficiency, e.g. by heat pumps, which can be up to 300% efficient. More electricity means less gas (29% in 2020 to 18.5% in 2050) and biomass (24% now and 14% in 2050).

Heat pumps will provide 51% of total useful energy for space heating and 20% for water heating, while using only 19% and 5% of final energy, respectively, in 2050. The growing energy demand for lighting and appliances (87% from now to 2050) is only partly offset by energy intensity improvements (0.6%/yr). Space cooling, amplified by global warming, quadruples by mid-century to take an 18% share of buildings energy demand.

Manufacturing
Energy demand rises 22% by 2050. Most growth occurs before 2030, plateauing at ~162 EJ/yr by mid-2030s.

Despite substantial energy-efficiency gains and increased recycling, manufacturing still has the largest share (30%) of final energy demand in 2050.

Energy demand for manufactured goods climbs 26% to 2050 – driven by rising prosperity mainly in lower-income regions. Fossils fuels supply half of this demand now but are less than a third in 2050. The Indian Subcontinent surpasses Greater China to account for 30% of energy demand for manufactured goods in 2050.

Steel production is the biggest (31%) user of energy in manufacturing, but demand will plateau from 2040 owing to a 58% increase in electricity use, with 'green steel' accounting for 9% of hydrogen use in 2050.

In cement making, reducing the overall share of clinker will help energy demand to level off at some 12 EJ from 2030 (one EJ higher than today's level).

FIGURE 4

World buildings energy demand by carrier

Units: Percentages

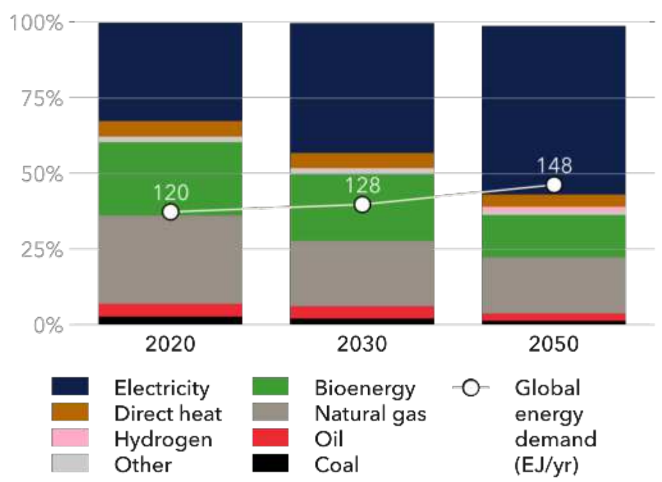
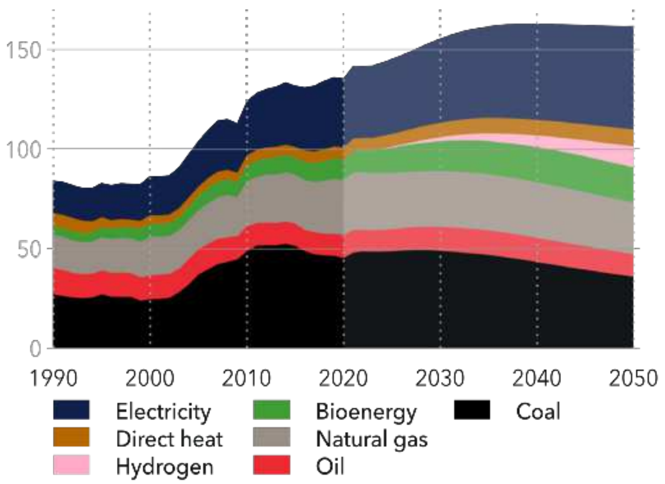


FIGURE 5

Manufacturing energy demand by energy carrier

Units: EJ/yr



Historical data source: IEA WEB (2022)

Increased recycling dampens energy demand growth in non-ferrous base materials (principally aluminium and wood-based products), but mining and construction will see the highest relative growth from 6 EJ now to 9 EJ in mid-century.

Feedstock
Feedstock demand for natural gas remains consistent at around 18 EJ, while non-energy oil demand rises from some 22 EJ to peak at 28 EJ before returning to today's level by 2050. Demand increases are driven initially by plastics and bitumen, outpacing a decline in lubricants in road transport. But ever-higher plastic recycling rates, due to regulations and technology advances, will see demand for virgin resin fall from the mid-2030s, even as plastic end-use demand rises from 450 Mt per year in 2020 to 860 Mt per year in 2050.

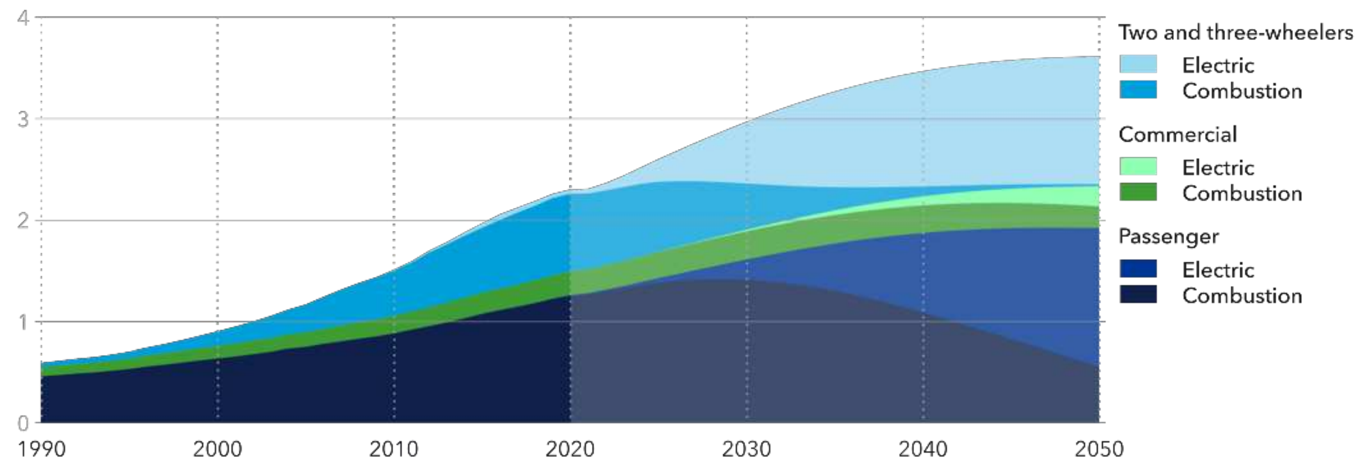
Transport
Although transport services will grow significantly in the next 30 years, overall energy demand in the transport sector will grow only slightly from 105 EJ/yr in 2020 to 114 EJ/yr in 2050. Between 2021 and 2050 there will be a 45% fall in the use of oil for transport – 24 million barrels of crude oil per day will disappear from this demand subcategory. This is strongly associated with the switch from internal combustion engines to battery-electric drivetrains, with half the world's fleet of passenger vehicles electrified by 2043. Efficiency gains in the road-transport sector will more than counterbalance growth in energy demand in aviation. This trend will also be helped by significant energy-efficiency gains in the maritime sector that lead to a peak in its energy use in the mid-2030s, despite growth in the size of the world fleet.

Road transport: Electrification will transform road transport in the next three decades. EV uptake will be rapid. The two- and three-wheeler segment will be almost completely electric by 2040. EVs will reach 50% of new passenger vehicle market share in Greater China and Europe in the late 2020s, in the early 2030s in OECD Pacific and North

FIGURE 6

World number of road vehicles by type and drivetrain

Units: Billion vehicles



Combustion vehicles include ICEs and PHEVs. Electric vehicles include BEVs and FCEVs.
Historical data source: Marklines (2022), IEA EV Outlook (2022), EV Volumes (2022)

America, and globally by 2033. Battery costs are the key driver of EV competitiveness, and these will keep falling in line with a technology cost-learning rate of 19% for every doubling of capacity. Electrification will be more prolonged for commercial vehicles, which rely on much heavier and thus more costly batteries, but commercial EV sales will still surpass ICEV sales in frontrunner regions (Greater China and Europe) before 2030 and worldwide by 2040.

The size of the passenger vehicle fleet will expand by two thirds between now and 2050, and vehicle-kilometres driven will more than double. Nevertheless, due to the energy efficiency of EVs, overall energy demand from road transport will fall by 9%. In 2050, 78% of all vehicles will be electric, but will account for just 33% of road subsector energy demand.

Drivers of EV uptake towards 2050

Today, new EVs tend to be priced higher than their combustion counterparts, which is why many countries have subsidies and incentives to support their uptake. EVs will become significantly cheaper within a decade and remain cheap. As scale advantages for manufacturers erode, combustion vehicle prices are likely to rise.

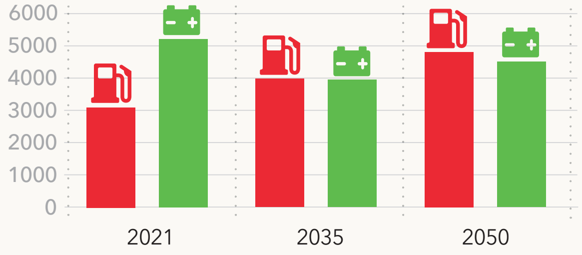
Despite the fact that EVs already have much lower running costs per 100 km, private buyers mainly look at purchase price. As upfront costs decline and total cost of ownership (TCO) advantages become clearer, passenger and commercial EVs will soon outcompete combustion vehicles. Unlike private buyers, commercial owners are strongly motivated by TCO calculations.

While EVs have already plunged through the fossil TCO line, buyer behaviour lags cost developments as other considerations like range and ease of charging come into play.

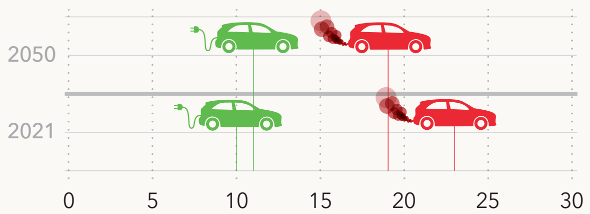
By 2050, 78% of all vehicles worldwide will be EVs. This will significantly alter road transport infrastructure. As ever more petrol stations are transformed into EV charging facilities, range anxiety may become an issue for combustion vehicles drivers.

Figures are based on OECD data, including 2021 average gasoline prices, electricity prices and vehicle costs. Vehicle operating costs include maintenance costs.

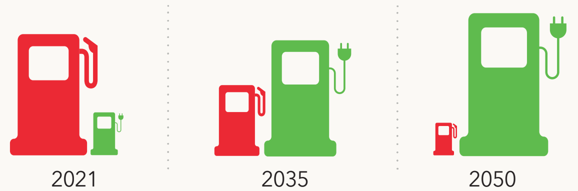
Annualized passenger vehicle price
Units: USD



Vehicle operating cost
Units: USD/100 km

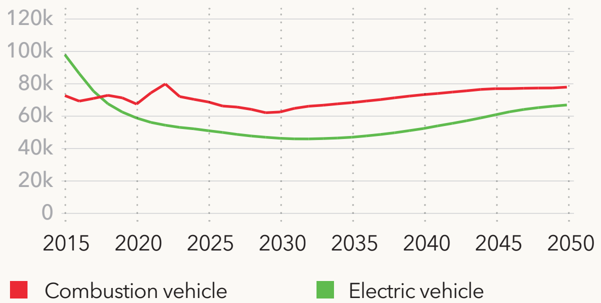


Relative availability of gas stations for Petrol and EV

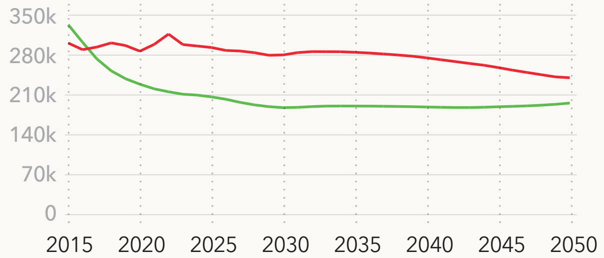


The size of stations are relative to each other for each year, and cannot be compared visually across years.

Passenger vehicle cost of ownership
Units: USD/Vehicle



Commercial vehicle cost of ownership
Units: USD/Vehicle



Aviation

With strong demand growth in China and South East Asia, passenger trips per year are likely to rise 140% above pre-pandemic levels by 2050, despite a re-basing of business travel 20% below our pre-pandemic forecast. Efficiency gains in engines, aircraft technology, and logistics will see fuel use rise by only 40%.

Despite public pressure to decarbonize, options for doing so remain expensive and challenged by availability of alternatives. Due to battery weight, electricity is suitable only for short-haul and some medium-haul flights. Short-haul uses a minor part of aviation fuel, and thus electricity is likely to cover just 2% of the aviation fuel mix in 2050. Green hydrogen is an attractive option in some ways, but the need for storage requires very large aircraft design and infrastructure changes that will limit uptake to 4% of aviation energy demand by 2050. Deeper progress will be made with sustainable aviation fuels (SAF), either bio-based or hydrogen-based derivatives, but cost will limit uptake to 13% of the energy mix. That leaves oil still dominant by 2050, but 26% lower than now in absolute terms.

Maritime

Nearly 3% of global final energy demand, including 7% of the world's oil, is presently consumed by ships, mainly by international cargo shipping. The IMO targets a 50% absolute reduction in CO_2 emissions between 2008 and 2050. We expect this to be met through a mixture of improved fleet and ship utilization, wind assisted propulsion, onboard CCS, energy efficiency improvements and a massive fuel switch (Figure 8). Potential for electrification in the maritime sector is limited.

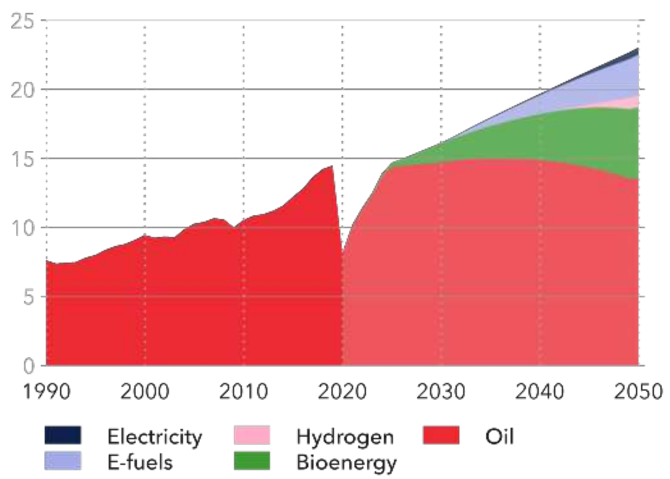
A world in which GDP doubles by 2050 will see cargo transportation needs considerably outweighing efficiency improvements. Cargo tonne-miles will therefore increase in almost all ship categories, with a total growth of 35% between 2020 and 2050. Important shifts include coal transport halving by 2050 in tonnes, and crude oil and oil products transport reducing by 20%.

From being entirely oil-based today, the 2050 fuel mix is 50% low- and/or zero-carbon fuels, 19% natural gas (mostly LNG) and 18% biomass. Ammonia has 35% of low-and/or zero-carbon fuels and e-fuels 15%. Electricity will have only 2%. See DNV's *Maritime Forecast to 2050* for details.

FIGURE 7

World aviation subsector energy demand by carrier

Units: EJ/yr

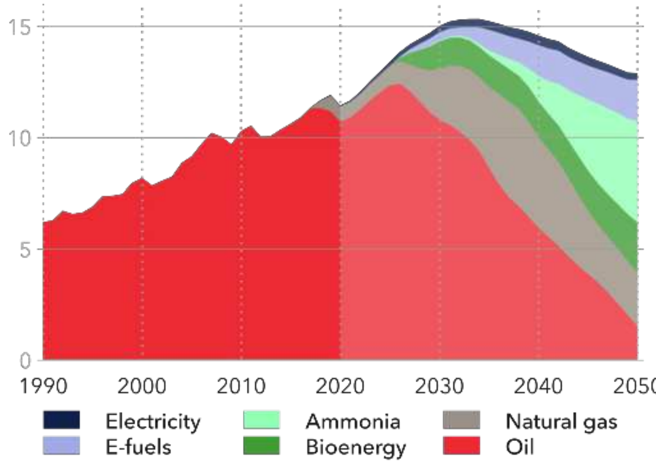


Historical data source: IEA WEB (2022)

FIGURE 8

World maritime subsector energy demand by carrier

Units: EJ/yr



Natural gas includes LNG and LPG. Historical data source: IEA WEB (2022)

ENERGY CARRIERS

Electricity

Electrification is the main engine of the energy transition, with positive impacts on access to clean energy in much of the developing world. In the next 28 years, electricity demand will rise from 27 PWh/yr to 62 PWh/yr.

Not only will electricity transform almost every aspect of end use, but generation will green at the same time, with the proportion supplied by wind and solar PV rising from 11% now to close to 70% by 2050. Critically, electricity will also penetrate sectors that have hitherto been hard to electrify via green hydrogen, over half of which will be supplied by dedicated renewable sources by 2050.

Growing at almost 3% per year, electricity demand will outpace economic growth. This is due to vast new categories of demand totaling 14,000 TWh/yr by 2050. Of this new demand, the electrification of road transport (2.8 billion EVs by 2050) is responsible for half.

Electrolysers producing green hydrogen will take an 8% share of the total electricity demand, new space cooling requirements 12%, and almost 1.5 times of that share goes to the growing manufacturing subcategory of machines, motors & appliances.

With rapid retirements from 2026 onwards, coal will fall to almost 50% of its present capacity by 2050. Gas capacity reduces 21% from current levels. Increasingly, hydrogen will be blended in gas-fired power plants in the OECD regions.

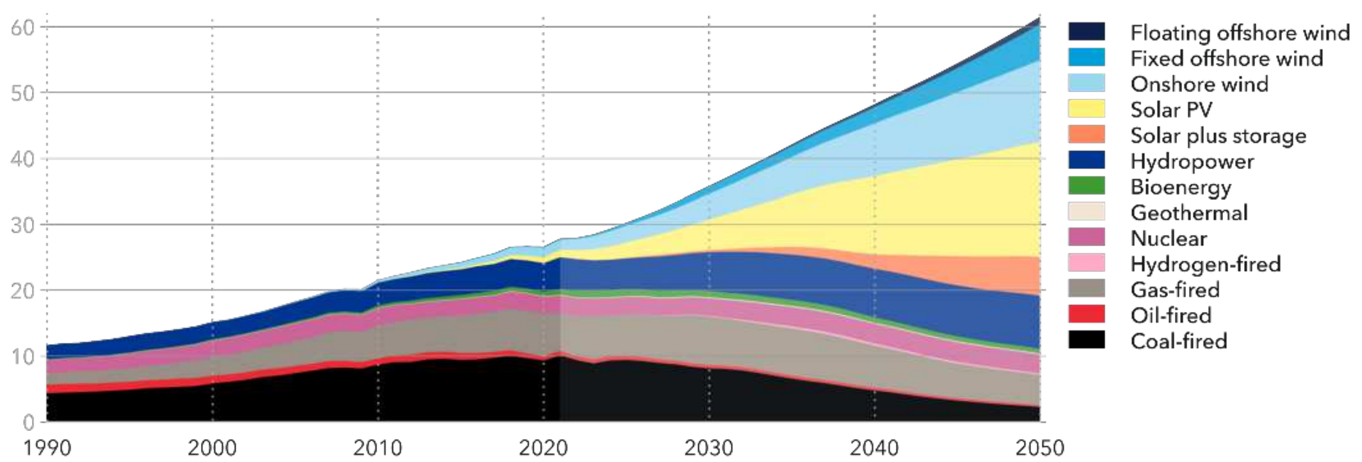
New nuclear capacity additions, largely in Greater China, compensate for retirements in Europe and North America. In relative terms, nuclear more than halves its share, dropping from 10% in 2019 to 5% in 2050. Hydropower will be limited by resource constraints, reducing its share in the global electricity mix from 16% in 2020 to 13% in mid-century.

Grid investments will rise by between USD 150–200bn/yr from pre-pandemic levels. In terms of circuit-km, transmission lines will triple and distribution lines more than double by 2050. The build-out is a response to the rapid growth in VRES and the fact that peak power demand grows slightly faster than power demand, at 3.1% per year. Of the transmission lines, HVDC lines will have a share of 20% by power capacity in 2050.

FIGURE 9

World grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2022), GlobalData (2022)

Hydrogen

Renewable and low-carbon hydrogen is crucial for meeting the Paris Agreement goal to decarbonize hard-to-abate sector, i.e. those that cannot easily be decarbonized through electrification. To meet the targets, hydrogen would need to cover some 15% of world energy demand by mid-century. We forecast that, largely for reasons of cost, global hydrogen uptake reaches just 0.5% of the global final energy mix in 2030 and 5% in 2050, although the share of hydrogen in the energy mix of some world regions will be double these percentages.

Even at 5% of global energy demand, developments in hydrogen over the next 30 years will be substantial, and in some cases, industry changing. Global spend on producing hydrogen for energy purposes from now until 2050 will be USD 6.8trn, with an additional USD 180bn spent on hydrogen pipelines and USD 530bn on building and operating ammonia terminals.

Demand for hydrogen as an energy carrier will rocket upwards from negligible levels today to well over 250 MtH_2 per year by 2050 – with demand climbing steeply by then. The bulk of hydrogen end use will be for manufacturing (61%), followed by transport (17%) and buildings (14%), with the remainder going to electricity generation and other uses. Hydrogen will be critical for the decarbonization of international shipping, with uptake of hydrogen-derived e-methanol of 360 PJ (2% of shipping fuel mix) in 2030, 1,400 PJ (10%) in 2040 and 1,800 PJ (14%) in 2050. Ammonia will likely have a lower initial uptake than e-methanol until 2040, but then scale faster from 1,100 PJ (8% of the shipping fuel mix) in 2040 to 4,500 PJ (35%) in 2050. We expect a 20-fold increase in ammonia seaborne transport between 2030 and 2050, with a total shipment of 150 million tonnes at that time.

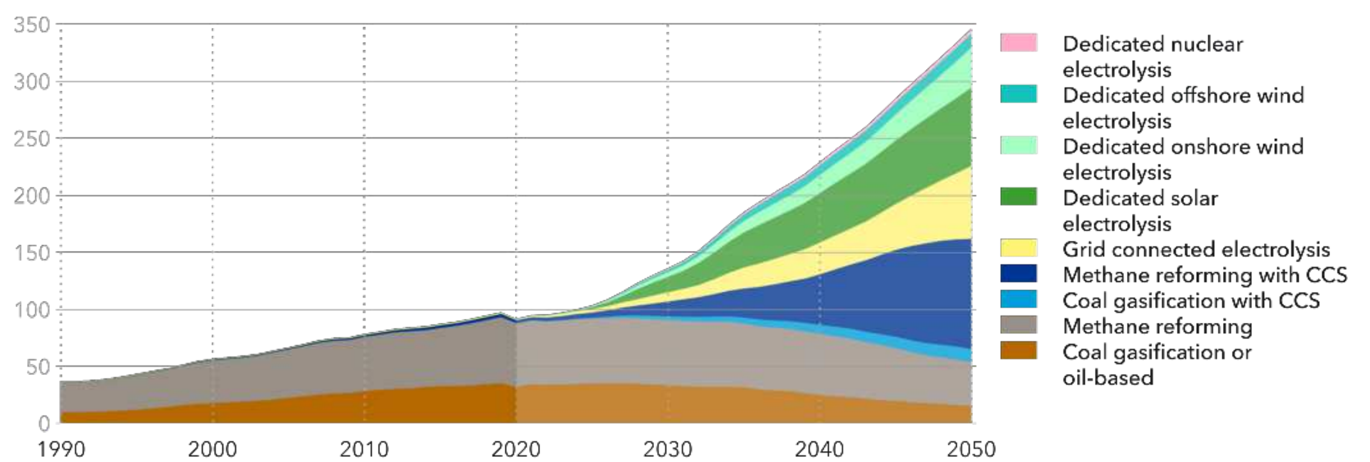
Figure 10 shows how future supply of low-carbon hydrogen progresses towards 2050 when 85% of the world's hydrogen supply will be from low-carbon routes, broken down as follows: 27.5% blue hydrogen, 25.5% from grid-connected electrolysis, 17.5% from dedicated solar-based electrolysis, 13% from dedicated wind-based electrolysis and 1% from dedicated nuclear-based electrolysis.

We refer readers to our detailed *Hydrogen Forecast to 2050*, described more fully on page 32.

FIGURE 10

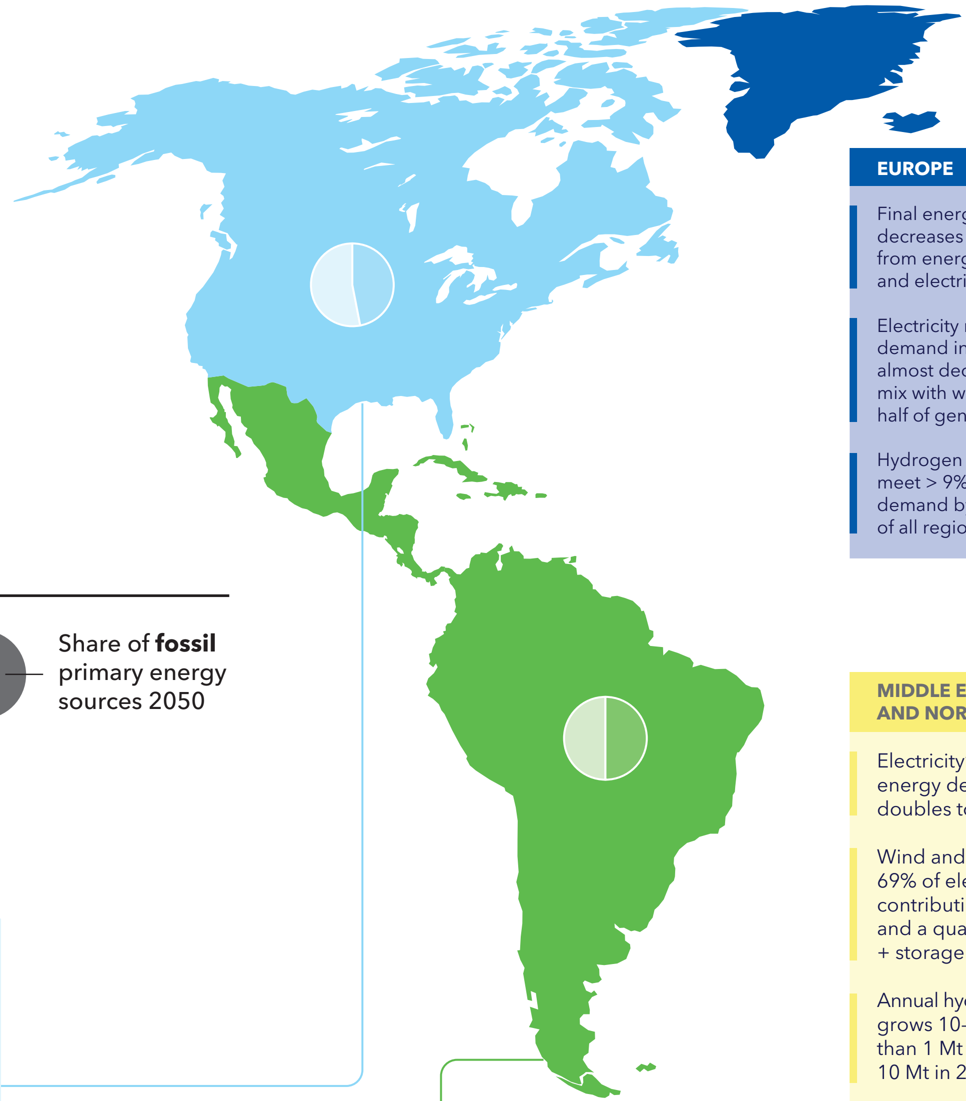
World hydrogen production by production route

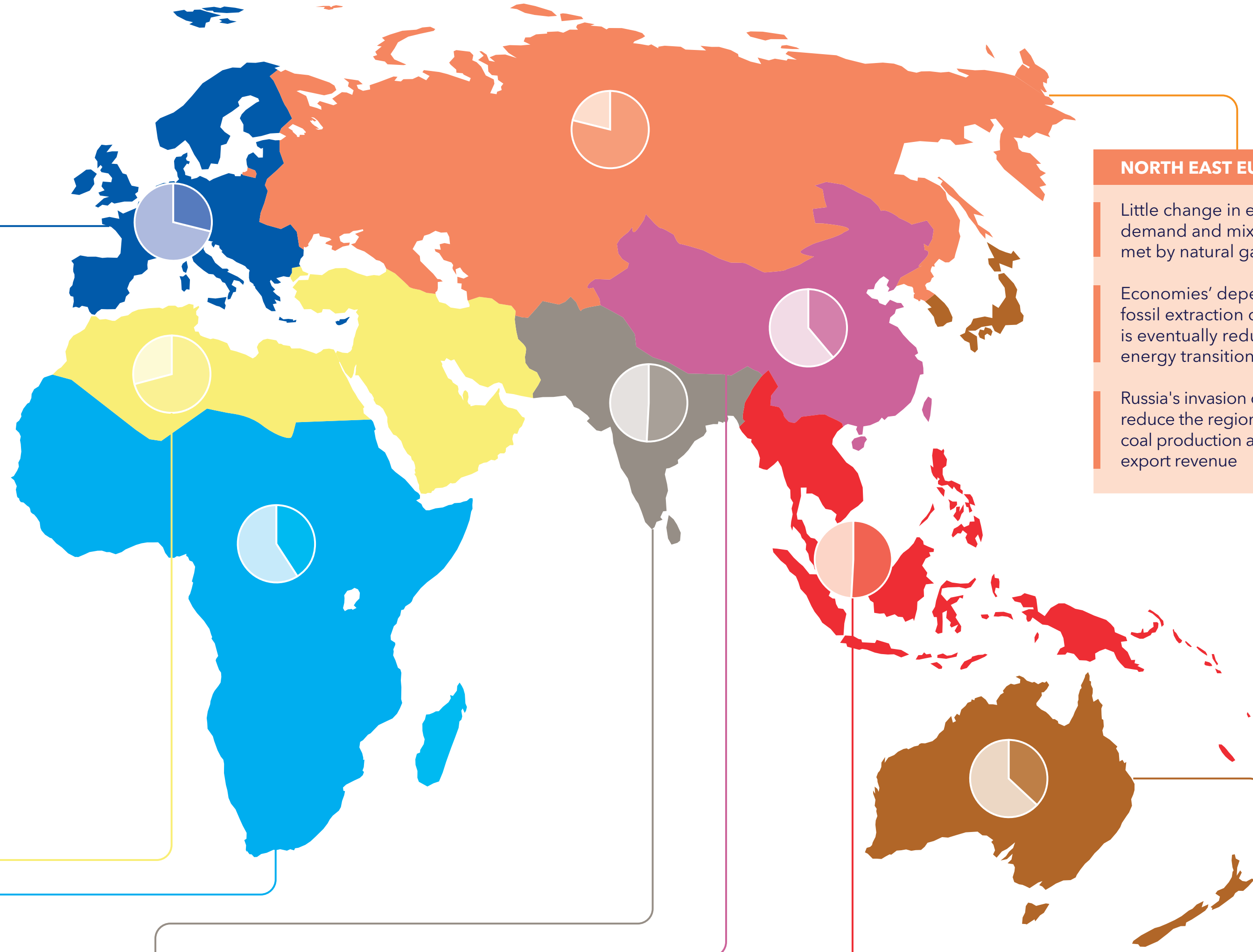
Units: MtH_2/yr



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

WE ANALYSE 10 GLOBAL REGIONS





KEY

Share of **non-fossil** primary energy sources 2050 — Share of **fossil** primary energy sources 2050

EUROPE

- Final energy demand decreases by 21% to 2050 from energy-efficiency gains and electrification
- Electricity meets 43% of demand in 2050 from an almost decarbonized power mix with wind accounting for half of generation
- Hydrogen and derivatives meet > 9% of final energy demand by 2050, the highest of all regions

MIDDLE EAST AND NORTH AFRICA

- Electricity's share of final energy demand more than doubles to 38% in 2050
- Wind and solar provide 69% of electricity, solar contributing almost 50% and a quarter of this in solar + storage plants
- Annual hydrogen production grows 10-fold from less than 1 Mt in 2030 to nearly 10 Mt in 2050

NORTH EAST EURASIA

- Little change in energy demand and mix, majority still met by natural gas in 2050
- Economies' dependence on fossil extraction continues, but is eventually reduced by energy transition elsewhere
- Russia's invasion of Ukraine will reduce the region's gas and coal production and lower oil export revenue

NORTH AMERICA

- Natural gas dominates manufacturing energy mix through to 2050, while buildings shift to electricity for 70% of demand. Electricity meets 40% of final energy demand by 2050
- Electricity generation will not be carbon-free in 2035 – 34% still coming from hydrocarbons
- Emissions decline 67% to 2050 but transport becomes the largest emitter

LATIN AMERICA

- Fossil fuels will have a 47% share of final energy demand, dominated by oil (31%)
- Solar PV and wind power grow to account for 82% of power generation in 2050
- 25 Mt/yr of hydrogen and derivatives are exported by 2050, building on the lowest levelized cost for solar-powered hydrogen production

SUB-SAHARAN AFRICA

- Energy demand increases by 90% from the population almost doubling, and also driven by manufacturing
- Off-grid solar PV meets 45% of energy demand from appliances and lighting by mid-century
- Fossil-fuelled power will provide 20% of on-grid generation by 2050 with hydropower and other renewables accounting for 79%

INDIAN SUBCONTINENT

- By 2050, 53% of primary energy will come from fossil fuels, coal having a 22% share
- Demand for electricity grows 10-fold with electricity meeting 33% of final energy demand in 2050
- Solar and wind will have 67% of power generation combined, adding 3.4 TW capacity between 2030 and 2050

GREATER CHINA

- Electricity's share of energy demand doubles to 47% in 2050, the highest of all regions with >90% from renewable energy sources
- The share of coal in power generation (current 62%) reduces to 4% in 2050
- CO_2 emissions peak before 2030 and carbon intensity (tCO_2 per unit GDP) reduces 66% to 2030

SOUTH EAST ASIA

- Greatest exporter of coal at 400 Mt in 2020, and the coal sector is entrenched in region economies
- Electricity doubles its share in final energy demand to 36% by 2050
- Solar PV and solar + storage plants rise from the late 2030s to account for 74% of electricity in 2050

OECD PACIFIC

- By 2030, all capacity additions in power generation are from renewable energy or nuclear
- 72% of grid-connected electricity is based on renewable energy sources in 2050
- Hydrogen and its derivatives are 8% of final energy demand by 2050, the second highest share after Europe

ENERGY SUPPLY

The fall of fossil fuels
The fossil slice of the primary energy pie shrinks by around one percentage point per year, going from 80% now to just below 50% in 2050.

Coal – peaked at 8 Gt per year in 2014. Since then, total demand for coal has and will decline. The pandemic reduced coal demand by 7% in 2020. The demand rebound will not reach its previous peak, instead coal use will fall almost two-thirds from current levels by 2050.

Oil – In 2020, demand was 75 million barrels per day (Mb/d) excluding natural gas liquids and biofuels. We predict a peak in 2025, at 86 Mb/d, 15% above today's level, before going into steady long-term decline. Demand will decrease slowly between 2025 and 2035, after which the decline becomes relatively steep, averaging -2.4% per year over the period 2035–2050. In 2050, expected global oil demand of 56 Mb/d (115 EJ) will be 32% lower than today. This decline is linked largely to falling demand in the transport sector, down 45% in the next 28 years. Production will be concentrated ever more strongly in Middle East and North Africa.

Natural gas – peaks in 2036 and slowly tapers off to end some 10% below today's levels. It surpasses oil as the largest source of primary energy in the late 2040s. Gas has staying power owing to its diversity of uses – half of the demand for gas is as final energy in manufacturing, transport and buildings, and the other half through transformation for other final uses like electricity, petrochemicals and hydrogen production. Demand will vary considerably across regions: declining in OECD countries, growing in Greater China, but peaking there in the early 2030s, and tripling in the Indian Subcontinent by 2050.

By mid-century, just 12% of gas will be carbon free, of which hydrogen will supply roughly one quarter, with the balance made up through CCS in power and industry, and by biomethane. In modelling gas demand, we assume that today's high prices persist through 2024 before gradually returning to 2021 levels. Sensitivity tests run with high prices lasting for six and up to 12 years show how that will damage the outlook for gas globally and in Europe in particular – where its use will halve within a decade.

FIGURE 11

Fossil vs. non-fossil in primary energy supply

Units: Percentages

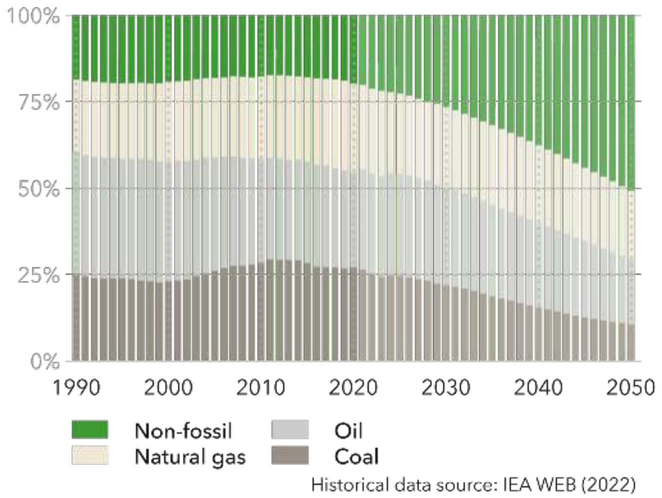
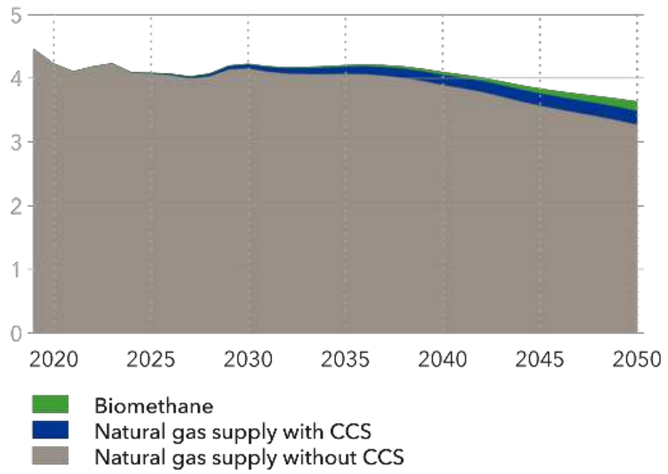


FIGURE 12

World natural gas and decarbonized gas supply

Units: Tm^3/yr



The rise of renewables
Coal and gas decline to 4% and 8% respectively of the power mix by 2050, when they are largely confined to providing flexibility and backup in a power system 70% reliant on variable renewable energy sources (VRES).

From today to 2050, solar capacity increases 22-fold, wind capacity 9-fold, onshore wind 7-fold, and offshore wind 56-fold. Driving this are both plunging costs and a growing realization that VRES offer the cheapest and quickest route to both decarbonization and energy security.

The global weighted average levelized cost of energy (LCOE) for **solar PV** is currently around USD 50/MWh for solar and USD 120/MWh for solar+storage. This reduces to around USD 30/MWh by mid-century for solar PV, with individual projects well below USD 20/MWh. Solar+storage cost is currently more than double that of solar PV without storage. Falling battery prices will narrow this gap to around 50% by mid-century.

Within a decade, about one fifth of all PV will be installed with dedicated storage, and by mid-century this rises to half. Global annual solar installations will reach some 550 GW per year of net capacity additions by 2040.

LCOE for fixed and floating offshore **wind** reduces 39% and 84%, respectively, in our forecast period. Even relatively mature onshore wind sees cost reductions of 52%. These developments fuel the rise of on-grid wind from 1,600 TWh/yr in 2020 to 19,000 TWh/yr in 2050. By 2050, wind will provide almost 50% of on-grid electricity in Europe, and 40% in North America and Latin America.

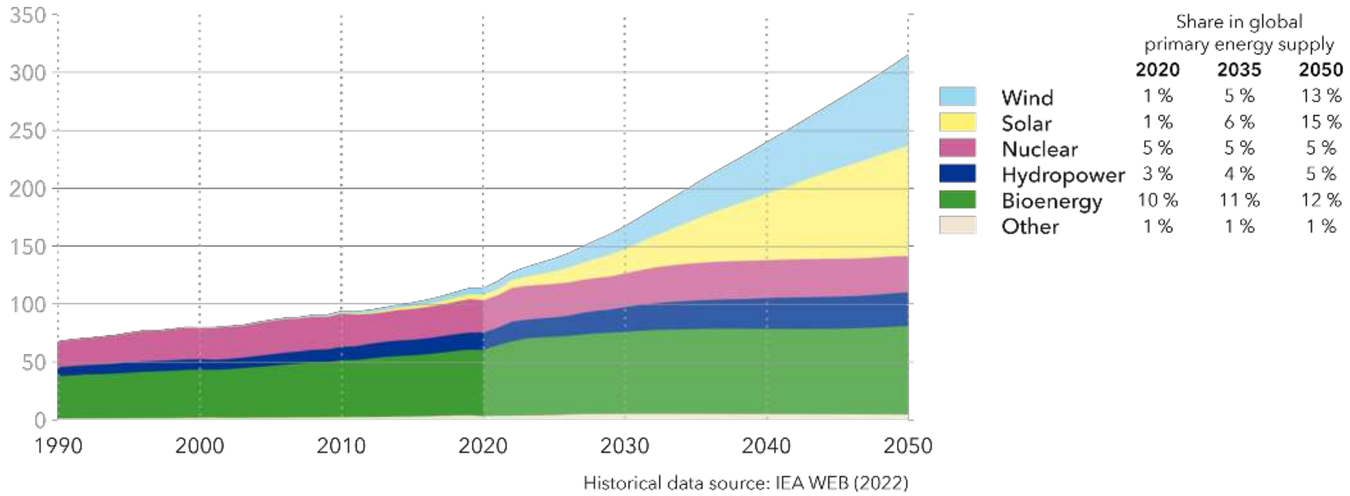
In a world seeing doubling of electricity generation by 2050, **hydropower** generation will still provide 13% of total electricity supply, down from 16% in 2020. While growing in absolute terms, this loss of share is transferred to solar and wind.

Waste management and high construction costs and long lead times remain stubborn realities for **nuclear** power. However, current energy security concerns are leading to renewed interest in this source, and our forecast this year reflects a modest uptick in nuclear, growing by 13% from today's levels to 2050.

FIGURE 13

World non-fossil energy supply by source

Units: EJ/yr



Wind: Grid electricity from wind increases from 1.6 PWh/yr in 2020 to 19 PWh/yr in 2050, with Greater China, Europe and North America leading in output, and OECD and Latin America growing sharply from 2030. Europe and OECD Pacific will have the highest shares of offshore wind.

New turbine types and bigger turbines, blades, and towers will raise capacity factors for onshore wind from 26% now to 34%, and from 38% to 43% for offshore wind by 2050. This, together with cheaper turbines, are the main drivers of cost reductions of 52% for onshore wind over the period 2020 to 2050, with fixed and floating offshore costs dropping 39% and 84%, respectively. Of the 6 TW of installed capacity in 2050, 1.8 TW will be fixed and 289 GW floating offshore.

Solar PV: The growth of solar PV has been remarkable: 1 GW per year was installed for the first time in 2004, 10 GW added in 2010, and 100 GW in 2019. In 2021, 150 GW was added despite supply-chain disruptions due to COVID-19. From 2030 onwards, we expect annual additions of between 300 and 500 GW. By mid-century, total installed capacity will be 9.5 TW for solar PV and 5 TW for solar + storage. The resulting 14.5 TW of solar capacity is 24 times greater than in 2020.

We expect the average LCOE of solar PV to fall by at least 40% by 2050, with individual projects falling by as much as 60% relative to today's average cost. With its high cost-learning rates (26% at module level per doubling of capacity, declining to 17% in 2050), solar PV will be the cheapest source of new electricity globally by a considerable margin, despite its lower capacity factors relative to other VRES sources. By 2050, 23 PWh/yr of solar electricity will be generated worldwide.

Grids: Total grid investments have averaged USD 450bn/yr in the past decade. The expansion of renewable power leads to a steady increase in grid investments, reaching levels of USD 500bn/yr in the 2030s, and growing up to USD 1.1trn/yr by 2050. Measured by circuit-kilometres, transmission and distribution lines will almost triple during our forecast period.

FIGURE 14

Share of wind power in five leading regions in 2050

Units: Percentages

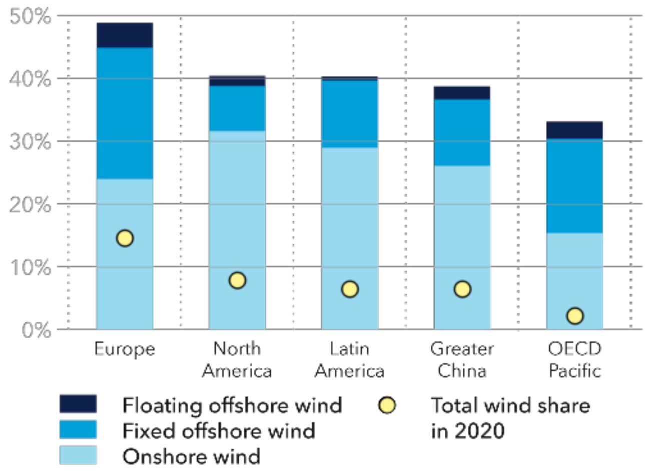
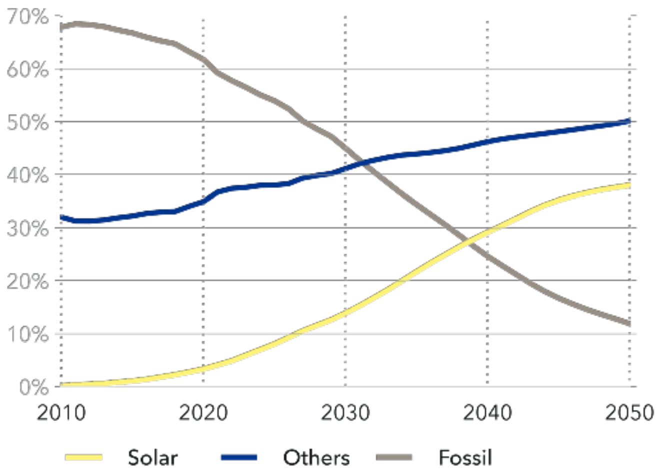


FIGURE 15

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

Units: Percentages



Historical data source: IEA WEB (2022)

Flexibility and storage

Flexibility: With a 16-fold increase in global VRES capacity by 2050, the need for flexibility will increase between two- and four-fold across regions.

Not all thermal sources are uniformly conducive to providing power system flexibility – ranging from nuclear where flexibility is challenging but not impossible, followed by coal, gas and oil-fired plants which are increasingly more flexible but costly. Equally important will be the ability of thermal plants to run economically at predominantly low load factors. Adapting for flexibility requires both physical changes, and investment in automation and analytics to better predict renewable-power generation levels. New market designs will be needed that incentivize the flexible operation of thermal plants.

Demand-side flexibility – shifting electricity usage from peak periods to times of lower demand and reacting to excess renewable generation – will also play a critical role. Implementation of smart grid features will enable better management of energy flows. New technologies and market mechanisms will also allow ever more active consumers to provide flexibility in the form of demand response, vehicle-to-grid and behind-the-meter storage.

Converting VRES, and to some extent thermal sources like nuclear, to other energy carriers, such as hydrogen, is yet another option that will provide flexibility.

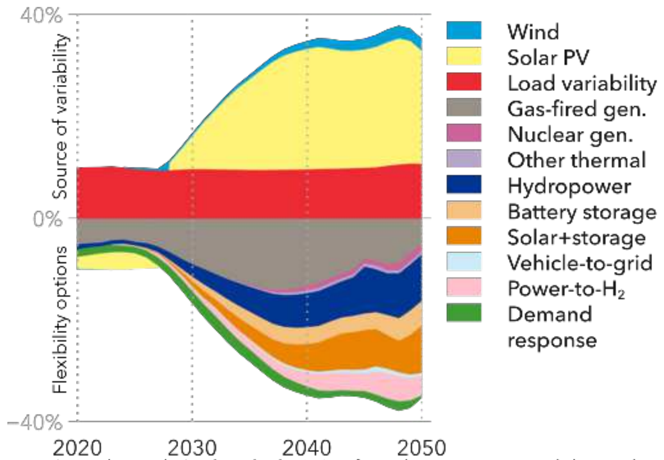
Storage: pumped hydro currently provides most of today's power system storage, but will only contribute marginally in the future. Batteries will provide most of the enormous future storage needs (Figure 17), either as standalone or in solar+storage or vehicle-to-grid configurations. From 2020 to 2050, standalone utility-scale storage will grow from 2.7 TWh to 8.8 TWh, more than doubling in size. Of this, Li-ion battery storage capacity will see the largest growth, from almost nothing to 4.4 TWh by mid-century. Towards the end of this decade, solid-state batteries appear to offer the best potential for a next wave in performance and cost improvements. Alternative chemistries will also evolve to satisfy the growing demand for longer-duration storage (5+ hours).

Over the longer term, costs for batteries will continue to plunge in line with a cost-learning rate of 19%, with more than 80% cost reduction between now and 2050.

FIGURE 16

Variability and flexibility in the North American power system

Units: GWh/GWh

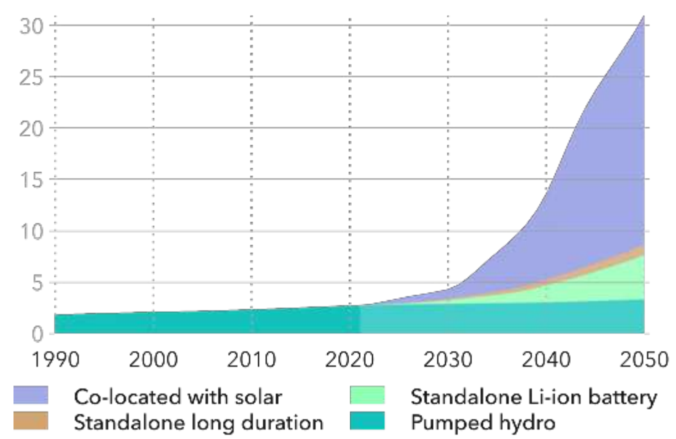


Annual cumulative hourly deviation from the average annual demand, relative to average annual demand.

FIGURE 17

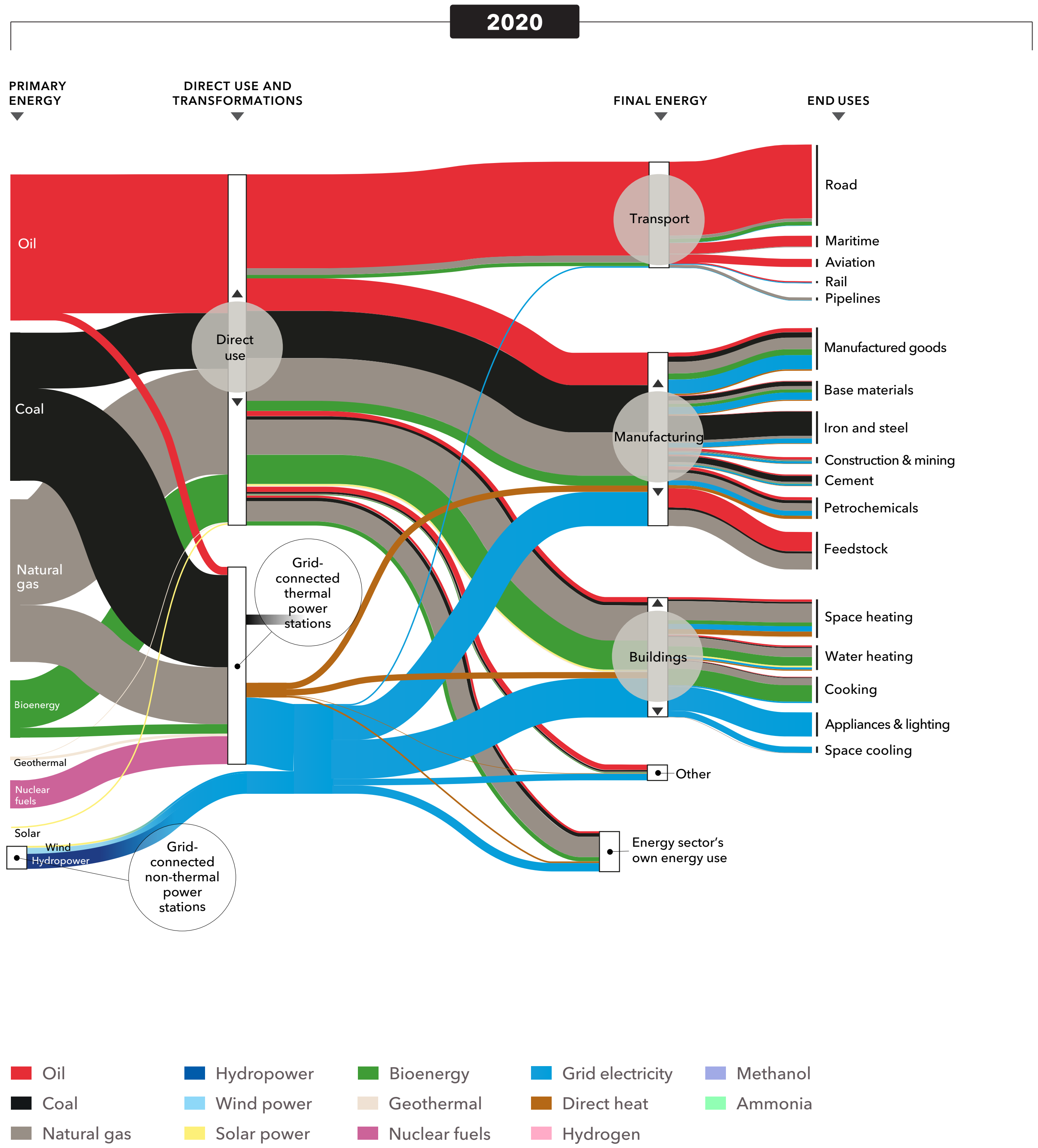
World utility-scale electricity storage capacity

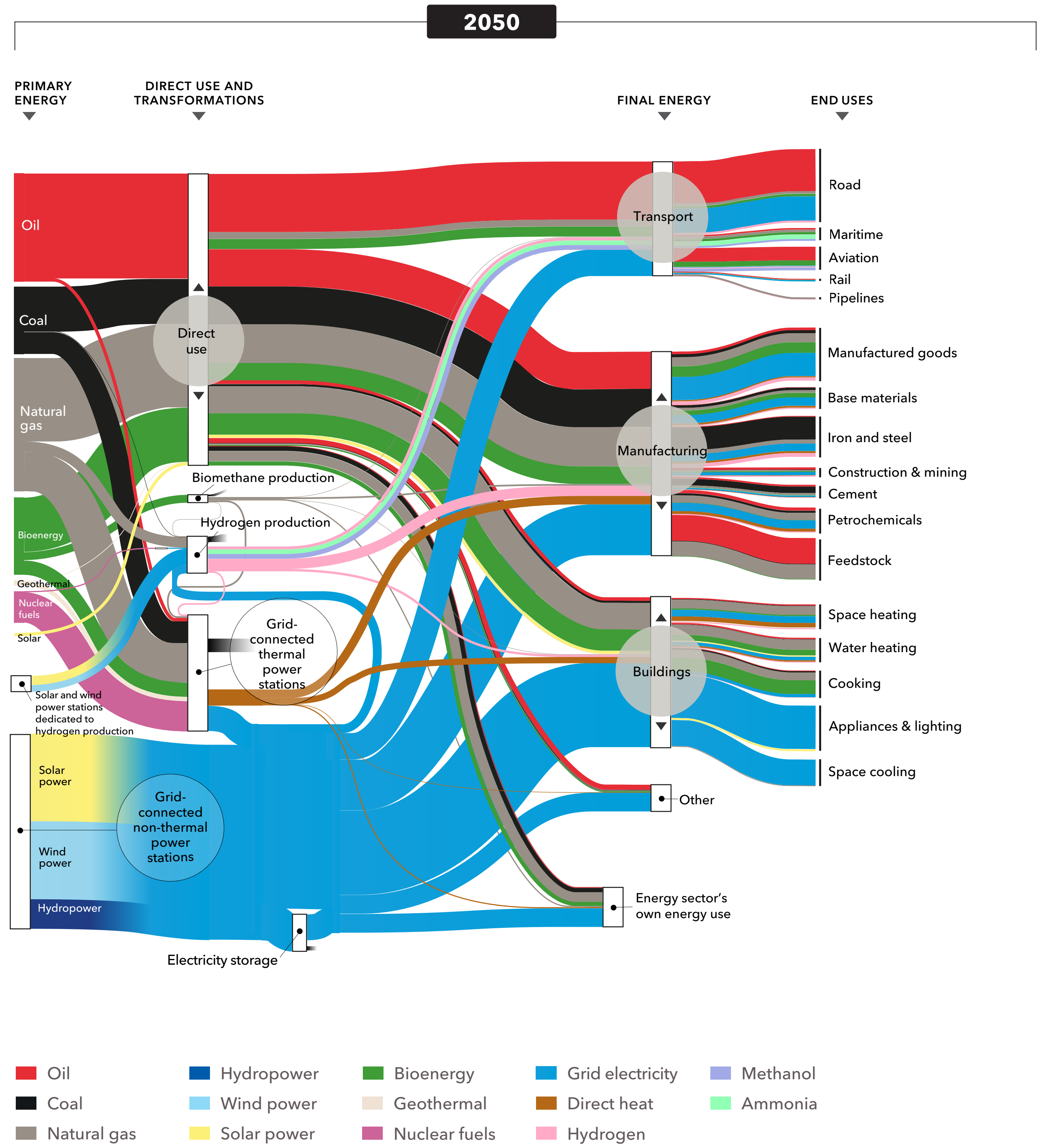
Units: TWh



Does not include behind-the-meter storage. Long duration storage includes 8-24 hours storage such as flow batteries, compressed air, liquid air, liquid CO_2 and gravity-based solutions. Historical data source: GlobalData (2022), US DOE (2022).

COMPARISON OF ENERGY FLOWS: 2020 AND 2050





ENERGY EFFICIENCY

High energy prices in 2022 have highlighted speed with which energy efficiency initiatives can significantly, and often permanently, ratchet down energy use and costs. Removing inefficient and expensive energy practices is a defining feature of the energy transition over the next three decades and should be the top priority for individuals, companies, and governments focused on transitioning faster and on achieving energy security.

The figure below plots energy intensity, population growth, and GDP per capita growth as annual average values within five-year intervals between now and 2050. After 2035, the reduction in energy intensity is stronger than the combined growth of population and GDP per capita. Hence, growth in global primary energy supply turns negative and primary energy supply peaks in the mid-2030s

Over our forecast period in which we foresee a doubling (107%) of global GDP and an 8% increase in primary energy consumption, energy intensity will be more than halved from 4.3 MJ/USD to 2.1 MJ/USD. In the 2040s, the intensity improvements taper off somewhat because, there will be fewer opportunities for further efficiency gains in power generation and energy end use.

Rapid electrification powered by renewables is the core driver of accelerating energy efficiency in the next three decades. The typical thermal efficiency for utility-scale electrical generators is some 30 to 40% for coal and oil-fired plants, and up to 60% for combined-cycle gas-fired plants. In comparison, solar PV and wind generation are 100% efficient, and conversion losses as a percentage of input energy in power generation reduce from 51% in 2019 to 19% in 2050.

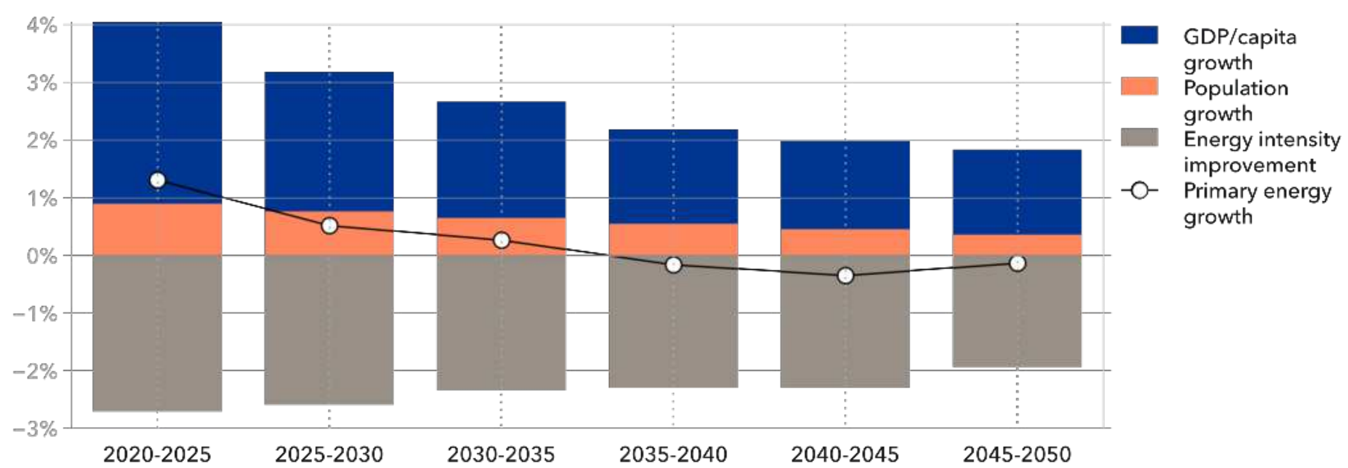
Most end-use efficiencies are also linked to electrification, for example EVs, which are three to four times more efficient than ICEVs. We also take into account technology improvements resulting in better engine performance, hull hydrodynamics or insulation. We find that without expected efficiency gains in transport, buildings, and manufacturing, energy demand would be 65% higher than we forecast for 2050.

There is potential to accelerate efficiencies beyond our forecast, but that will require new mandates from governments, action on demand side flexibility, and co-operation within industries on new standards and recommended practices.

FIGURE 18

World energy intensity and annual reduction rate

Units: Percentages/yr



ENERGY EXPENDITURES

The roll-out of renewables and grid build-outs will require very large upfront investment. Some therefore consider the transition to be 'unaffordable'. Our results suggest the opposite, with energy costs remaining stable and the share of energy expenditures in global GDP declining – from 3.4% in 2021 to 2.1% by mid-century. The energy transition thus involves a substantial green prize, paying dividends to society for generations to come, even before factoring in the avoidance of incalculable costs associated with climate damage.

Total world energy expenditure was USD 4.9trn in 2021. We project world energy expenditure to increase 26% to USD 6.2trn by 2050 – far below the 107% increase in global GDP over the same period. The unit cost of energy will stay stable around 11-12 USD/GJ even with a fundamental reshuffling in energy expenditure by source. Between 2021 and 2050, fossil expenditure will reduce 40% in USD terms, non-fossil will triple, and grids will also almost triple.

Our forecast includes shifts in cost of capital across various energy sources and regions. Although there are regional variations, the cost of capital is generally steepest for coal, increasing for oil and gas, stabilizing over time for variable renewables and nuclear, and declining for low-carbon and renewable hydrogen production. We project a structural shift away from fossil CAPEX and OPEX from the 2030s. Renewables CAPEX is almost twice as high as OPEX, despite the uninterrupted decade-to-decade increases in OPEX.

While the transition is affordable globally, expenditures on the provision of energy are not market prices paid by the consumer, which include margins, taxes and/or subsidies – and upfront investments in end-use items like EVs and heat pumps. However, we foresee that household energy expenditures in Europe and North America will remain high until energy supply shocks are alleviated around 2025, then returning to 2021 levels, in nominal terms. Subsequent decades will see stabiliza-tion of household energy expenditure at levels 10% less on average than in 2021, and gradually declining to 30% less by mid-century. This pattern does not apply to all regions, e.g. in the Indian Subcontinent, increasing electrification, especially with air-conditioners and higher energy consumption, sees its household energy expenditure gradually increasing to 30% above 2021 levels by mid-century.

FIGURE 19

World energy expenditures by source

Units: Trillion USD/yr

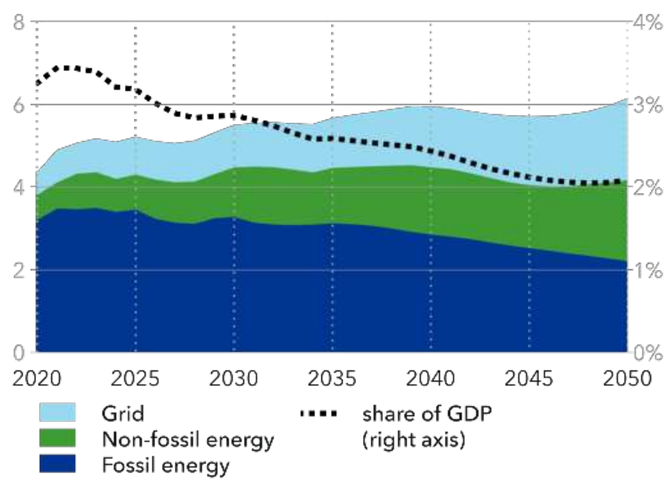
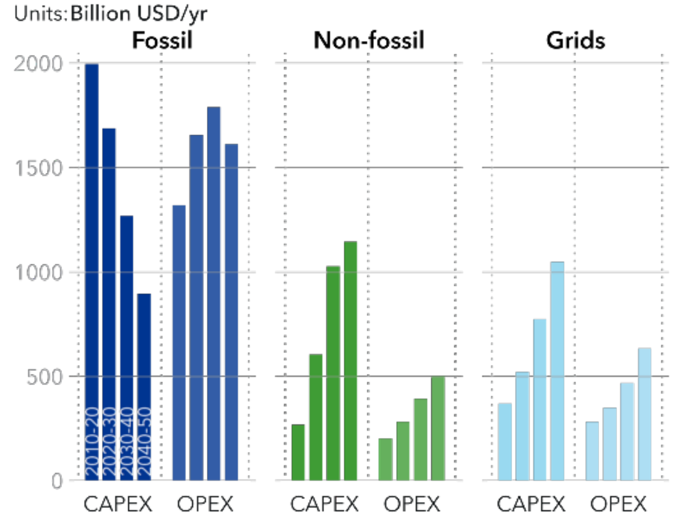


FIGURE 20

World energy CAPEX and OPEX, 10-year average

Units: Billion USD/yr



MODEL INPUT

Population

The number of people in the world is the key driver of energy demand. Energy use varies considerably per person across regions. For example, in Sub-Saharan Africa the average annual energy use per person currently stands at 24 GJ, but that will fall to 23 GJ/person/yr as the subcontinent electrifies. In Europe, the equivalent numbers are 121 GJ/person/yr (2020) and 97 GJ/person/yr (2050). Our 2050 population forecast is 9.4 billion people globally – an increase of 19% from the most recent UN (2021) population estimate of 7.9 billion.

GDP

World GDP is expected to grow from USD 134 trn/yr in 2020 to USD 296 trn/yr in 2050. This more than doubling is a result of the population increase and an 83% rise in average GDP per capita, with large regional differences. Compared to our forecast last year, the only region which has undergone a significant revision in terms of future GDP forecast is North East Eurasia (down 19% in 2030 and 16% less in 2050), due to the ongoing war in Ukraine. In 2023, the global economy will be 4.6% smaller compared to the pre-pandemic projections. The post-COVID-19 boost in 2023 will result in some regional economies growing slightly faster than they otherwise would have, and in 2050 the loss narrows to 2%.

Resource limitations

The energy transition we forecast will not be significantly constrained globally by the availability of either land/sea areas, water or raw materials. Narrowing the perspective, some regions may struggle to find raw materials and some land/sea areas may be constrained. The recent trend towards energy security and localization may exacerbate imbalances, which will be amplified under a more ambitious energy transition focusing on reducing emissions in line with a Paris-compliant 1.5°C future (see pages 30-33). We aim to revisit the topic of resource availability and understand the possible limitations that a net-zero future would entail in future research.

Policy

The energy transition is unfolding in a context of multiple geopolitical uncertainties, with key challenges being policies that advance energy security and diversification, while working to prevent climate change and protect planetary-boundary conditions. Today's central difficulty for policymakers is to manage short-term energy supplies without making decisions or investing in energy infrastructure that could undermine long-term societal goals.

The urgency of issues means that government interventions in energy systems are obligatory to spur structural change and emission cuts in time to achieve existing targets as well as net-zero ambitions. All policymakers have both a shared technology-opportunity space and a policy toolbox of known and proven measures that is available for forming their energy-system (re)development and transitions.

While policy analysis is challenging during a period of upheaval, the advancement of renewable energy has been resilient, showing record-breaking expansion in power systems world-wide. The huge, untapped potential for renewables in emerging markets is receiving heightened attention. In today's risk picture, companies and governments alike are increasingly hedging decisions against high prices to protect inhabitants and industry.

Compelling project economics and comparatively brief development lead-times to bring renewable plants on stream are helping to tilt policy support in favour of renewables in the short term, with long-term energy security as an additional motivation. Meanwhile, hard-to-abate sectors with limited opportunities for electrification need further government impetus to advance transitions; for example, hydrogen-based conversion projects and 'fit-for-purpose' regulatory frameworks.

Policy factors in our Outlook

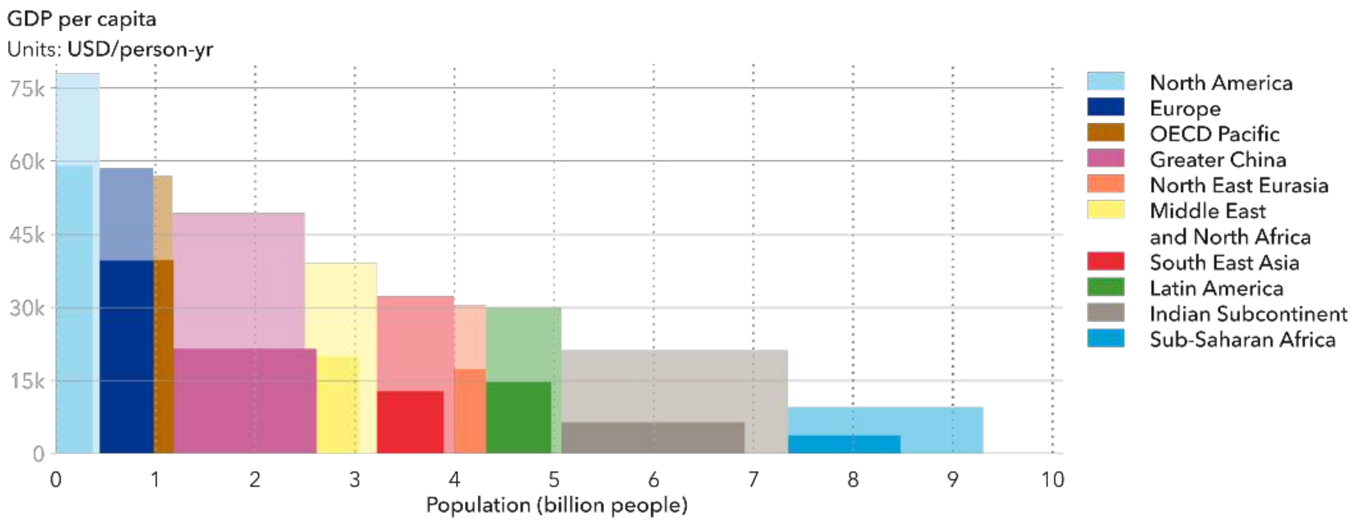
Policy influences all aspects of the energy system, and Figure 22 gives a snapshot of the policy factors incorporated into our forecast. Policy considerations exert influence in the following three main areas:

a) Supporting technology development and activating markets, thus closing the profitability gap for low-carbon technologies competing with conventional technologies;
b) Applying technology requirements or standards to restrict the use of inefficient or polluting products/technologies; or
c) Providing economic signals (e.g. a price incentive) to reduce carbon-intensive behaviour.

Country-level data are translated into expected policy impacts, then weighted and aggregated to produce regional figures for inclusion in our analysis.

FIGURE 21

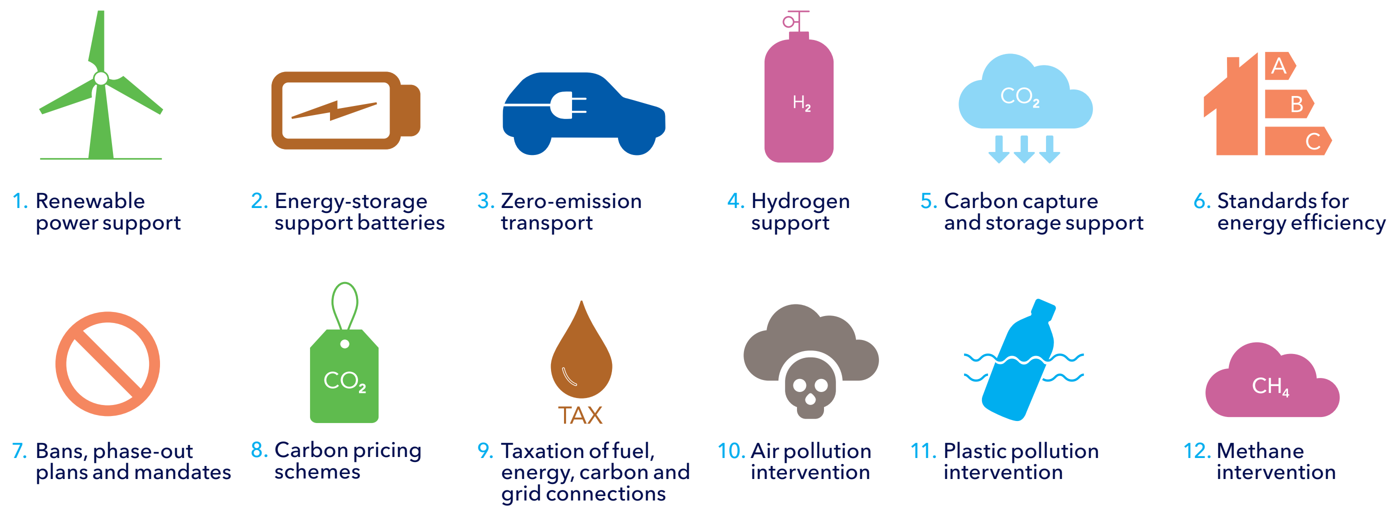
Change in population, GDP per capita and GDP between 2020 and 2050 by region



Darker boxes represent 2020, lighter boxes represent 2050. Historical data source: UN (2019), IMF (2022), World Bank (2018), Gapminder (2018)

FIGURE 22

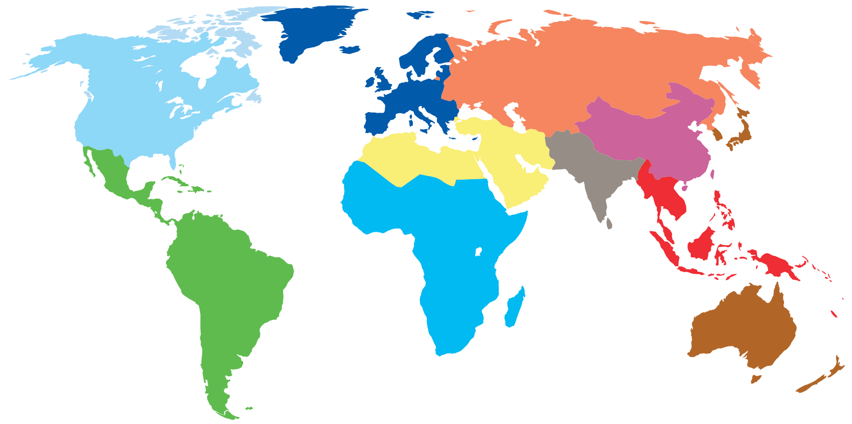
Policy factors included in our Outlook



GDP, ENERGY USE AND EMISSIONS ACROSS OUR 10 OUTLOOK REGIONS

2020-2050 Overview

This illustration shows, for each region considered in this Outlook, a comparison between per capita GDP, primary energy use and energy-related CO_2 emissions (2020 and forecast figures for 2050)



Region	Year	GDP per person (USD2017ppp/ person-yr)	Energy use per person (Gigajoules per year)	Energy-related CO_2 emissions per person (Tonnes per year)
North America (NAM)	2020	59 300	266	13.6
	2050	78 300	167	3.7
Latin America (LAM)	2020	14 800	49	2.2
	2050	30 100	60	1.7
Europe (EUR)	2020	38 800	121	5.4
	2050	57 500	97	1.2
Sub-Saharan Africa (SSA)	2050	3 800	24	0.8
	2050	9 600	23	0.8
Middle East and North Africa (MEA)	2050	20 100	90	5.0
	2050	39 300	96	3.5
North East Eurasia (NEE)	2020	17 400	140	7.4
	2050	30 500	132	5.8
Greater China (CHN)	2020	21 600	105	6.8
	2050	49 200	94	2.2
Indian Subcontinent (IND)	2020	6 500	25	1.4
	2050	21 200	43	1.5
South East Asia (SEA)	2020	12 900	44	2.3
	2050	32 300	65	1.9
OECD Pacific (OPA)	2020	39 800	170	9.4
	2050	56 900	122	2.3
World	2020	17 300	75	4.0
	2050	31 700	67	1.9

PATHWAY TO NET ZERO EMISSIONS

Unlike our ETO forecast, which results in global warming of 2.2°C by 2100, our Pathway to Net Zero emissions (PNZ) is a 'back-cast' estimation of what is needed to achieve a net-zero energy system by 2050 with the aim of securing a 1.5°C warming future.

The gap

Our ETO forecast has 22 $GtCO_2$ of annual emissions in 2050. Taking those emission to zero is not enough. Even were we to bend the emissions trend to intersect zero at 2050, the 1.5°C carbon budget would be exhausted by 2029 (Figure 23). That means to return to a 1.5°C trajectory by 2100, the cumulative emissions between 2030 and 2050 – an 'overshoot' of some 300 $GtCO_2$ – need to be removed in the second half of this century. This involves a massive carbon capture and sequestration effort .

Non-CO_2 GHG emissions

While the majority (~65%) of global warming is associated with CO_2, other GHGs, including methane, also need to be controlled. This involves, for example, changes in agriculture or aerosol use. We do not model this but have chosen instead to use the IPCC scenarios in line with 'very low' and 'low' non-CO_2 GHG emissions estimates in our PNZ. The focus of our Pathway is on CO_2 emissions associated with energy use.

Closing the gap

Reaching net zero requires both a deceleration of emitting sources (coal, oil and gas) and an acceleration of low- or zero-emission technologies far beyond our ETO forecast. In addition, a very large scaling up of both carbon capture and storage (CCS), direct air capture (DAC) and nature-based solutions will be needed to remove the overshoot of emissions accumulated before 2050. Up to 7 $GtCO_2$ per year must be removed through to 2100.

Policy

Standards, mandates, bans, and deep economic support are inescapable to spur the structural change needed. Policies must emphasize near-term action on decarbonization options, and a much greater level of cooperation and funding across regions.

High GDP regions must move at faster pace to achieve the Paris target, aligning with the UNFCCC principle of Common but Differentiated Responsibilities. In general, our PNZ is highly reliant on a ramping up of carbon prices. By 2050, regional trajectories range between 50–250 USD/tCO_2, with carbon-border adjustment mechanisms driving convergence among leading regions, and pulling all carbon-price trajectories upwards across all regions.

Demand

Population and economic growth – the underlying drivers of energy demand – are two realities that cannot be wished away. Our PNZ retains the same population and GDP assumptions as our ETO forecast. However, it is feasible to achieve a reduction in energy demand of some 9% by 2050 within these constraints.

The greatest shift happens in transportation. In our PNZ, electrification of road transport is accelerated, and oil use is 66% lower than in our ETO forecast. It is a leading example of how efficiencies from more extensive electrification, and the rapid decline of fossil sources, reduce global energy demand. In aviation, a faster and deeper uptake of decarbonized fuels raises the cost of flights, which leads to fewer flights: 7.7bn vs. the 10.2bn per year by 2050 in our ETO forecast. A further notable demand-reducing change occurs in the cement subsector where a push towards low-carbon cement will be expensive, even with government support, and will dampen overall demand by 25% compared with our ETO forecast.

Energy carriers

Electricity: Grid-connected electricity supply grows to 78 PWh/yr in 2050, 26% higher than our ETO forecast. This is a three-fold increase from 2020, firmly establishing electrification as the fulcrum for reaching net zero.

Phase-out of coal is enforced in all the regions, but not at the same time. The increased demand is provided chiefly by solar and wind. These two sources account for 74% of our PNZ electricity mix by 2050. In total, non-fossil sources (renewables and nuclear) account for 90% of the generation, with the remaining electricity provided by

FIGURE 23

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

Units: $GtCO_2$/yr

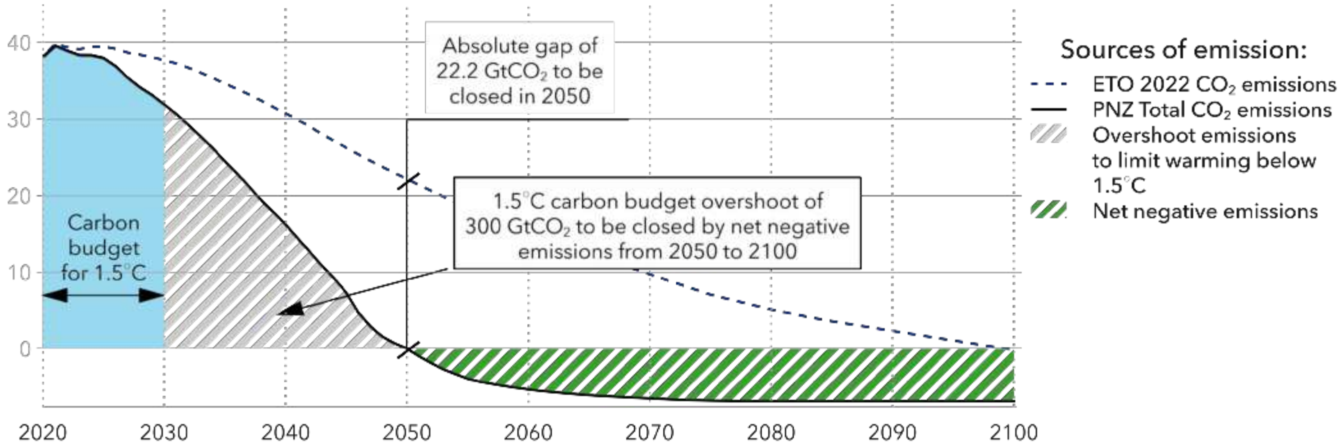
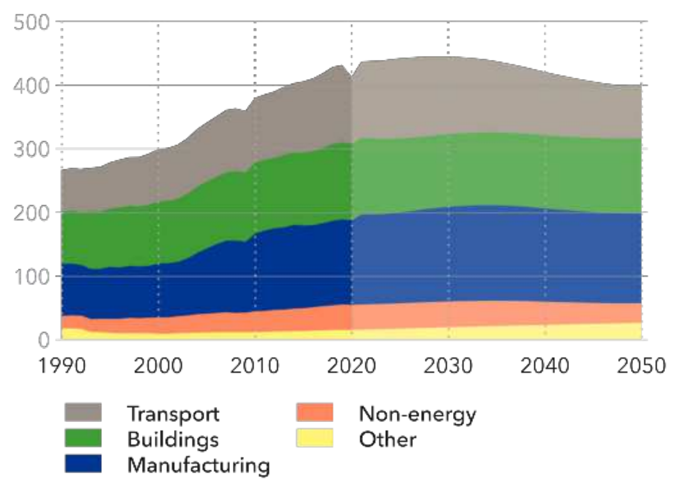


FIGURE 24

Final energy demand by sector – PNZ

Units: EJ/yr

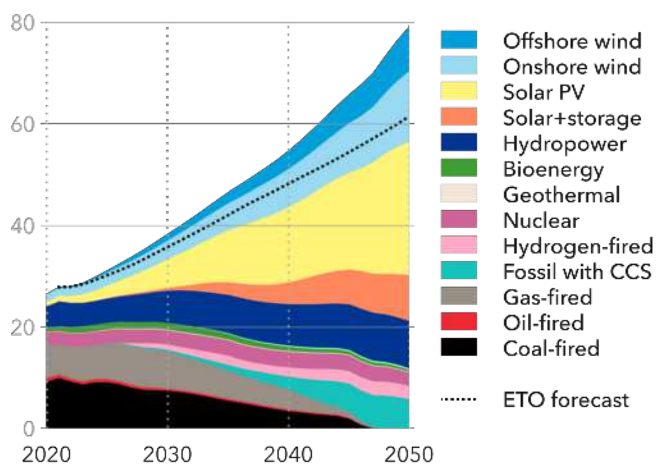


Historical data source: IEA WEB (2022)

FIGURE 25

World grid-connected electricity generation by power station type – PNZ

Units: PWh/yr



PATHWAY TO NET ZERO EMISSIONS

gas-fired power plants, most of them with CCS installed. Even under net-zero emission constraints, natural gas has staying power. Nuclear power remains around current levels through to mid-century.

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. Accordingly, our PNZ sees hydrogenand its derivatives supplying 14% of energy demand by 2050 - far higher than the 5% share in our ETO forecast.

This additional share is applied mainly to hard-to-abate sectors: industrial heat takes one third of PNZ hydrogen demand; heavy road transport 16%; aviation 12%; and maritime 15%. By mid-century, 80% of hydrogen will be green – 46% from dedicated off-grid capacities , led by offshore wind, and 34% grid-based electrolysis. 15% will be supplied from natural gas with CCS, leaving the share of non-carbon free hydrogen at less than 5% of the PNZ hydrogen mix by 2050.

Primary energy

Primary energy supply slowly reduces to around 95% of the present level by 2050. The energy mix will change dramatically: fossil use reducing from a 79% share today to 23% in 2050, implying a fossil share decline averaging 2% per year.

In 2050, fossil-fuel use in PNZ has less than half the share predicted in our ETO forecast. Still, a mid-century share of 23% is considerable, and will be accompanied by carbon capture for most major point-emission sources to reach net-zero emissions.

Fundamental to the PNZ is a massive ramping up of variable renewables energy, with solar (31%) and wind (20%) together constituting more than half the energy mix, and strong growth also seen for bioenergy and hydropower.

Net-zero expenditures

Figure 27 shows how fossil expenditures drop in line with an 80% decline for upstream oil and gas through to 2050. This offsets to some degree the very large investments needed in renewable power sources, storage, and grid build-out. Through the 2040s, the PNZ requires additional expenditures of some USD 600bn annually. However, total energy expenditures under the PNZ will still be a substantially smaller percentage of GDP than the world currently spends on energy. The costs associated with the PNZ are not unassailable.

CCS and direct air capture (DAC)

Not included in the modelled expenditures shown in Figure 27 are the costs of technologies and business models involving CCS and DAC. CCS is unavoidable for process emissions and abates most of the remaining fossil-fuel combustion emission. It will account for an annual spend reaching USD 23bn in 2030 and USD 270bn in 2050. DAC is less efficient than CCS and even though CCS will capture 3.7 times more CO_2, DAC will account for a higher annual spend, reaching USD 750bn in 2050. Together, CCS and DAC spending will represent 0.3% of global GDP in 2050. When net-zero emissions are reached in our PNZ, 2.6 $GtCO_2$ of energy and process emissions still remain unabated by CCS, notably in the transport sector. We expect that around 1.6 Gt of these lingering emissions would be captured via DAC technologies and stored.

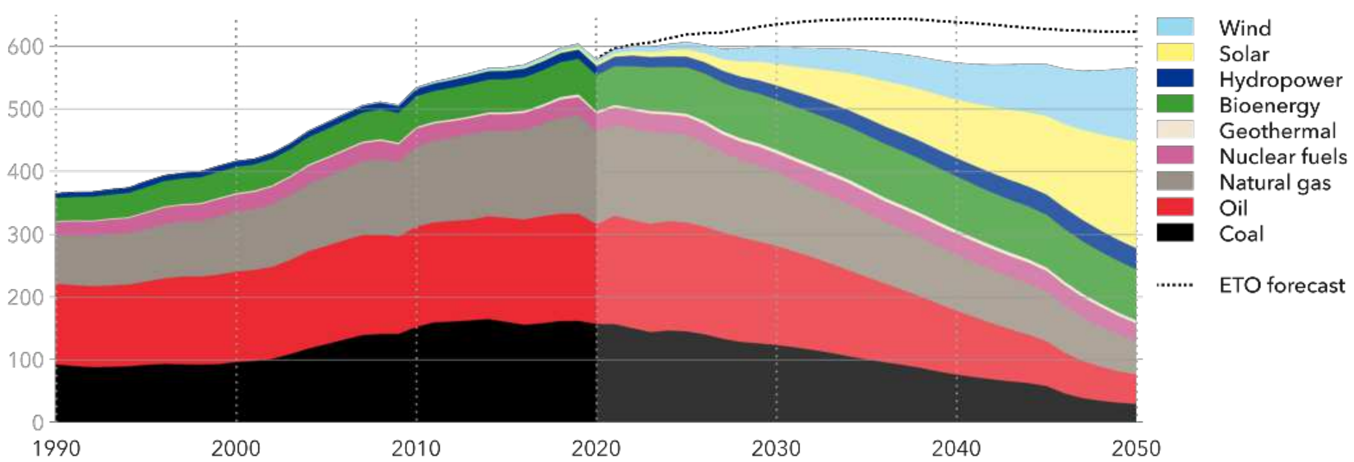
Regional pathways for net zero

Regions differ widely in terms of their starting position and ability to decarbonize. Broadly speaking, high income regions will need to go below zero before 2050 and in doing so scale low-carbon and carbon removal technologies. This enables lower-income regions to benefit from scale economies and technology transfers in managing their net zero targets after 2050. For example, both Europe and North America must achieve net zero by 2043 and thereafter achieve net negative emissions. This is a heavier undertaking for the more carbon-intensive energy system in North America, involving, for example, double the amount of solar and wind installations compared with the ETO forecast. Greater China will need to bring forward its net zero ambition to 2050 by halving its projected coal use and investing extensively in CCS. Latin America is an example of a low-income region that would need to achieve a net zero future in the decade after 2050 by electrifying transport and halving projected oil demand while achieving net negative power sector emissions through bioenergy with carbon capture and storage (BECCS).

FIGURE 26

Primary energy supply by source - PNZ

Units: EJ/yr

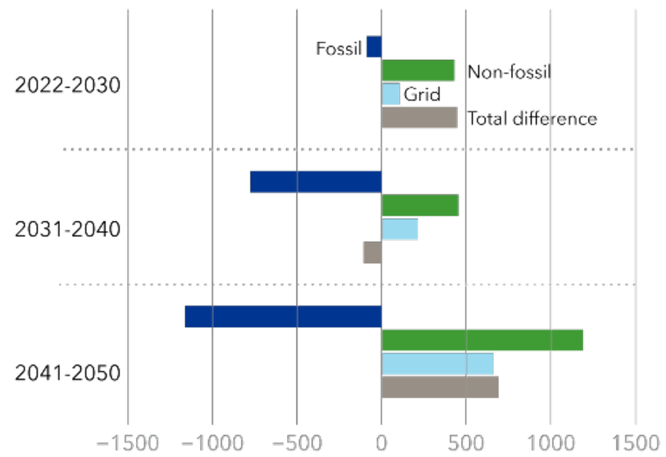


Historical data source: IEA WEB (2022)

FIGURE 27

Average difference in world energy expenditures between PNZ and ETO

Units: Billion USD/yr

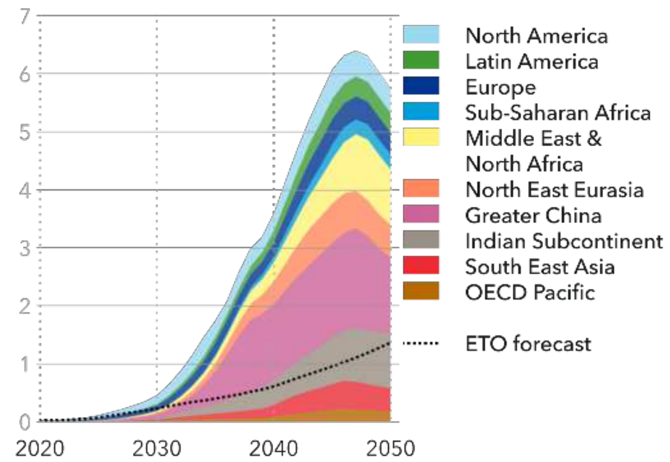


Positive value: higher expenditures in PNZ; negative value: lower expenditures

FIGURE 28

Emissions captured with CCS by region – PNZ

Units: $GtCO_2$/yr



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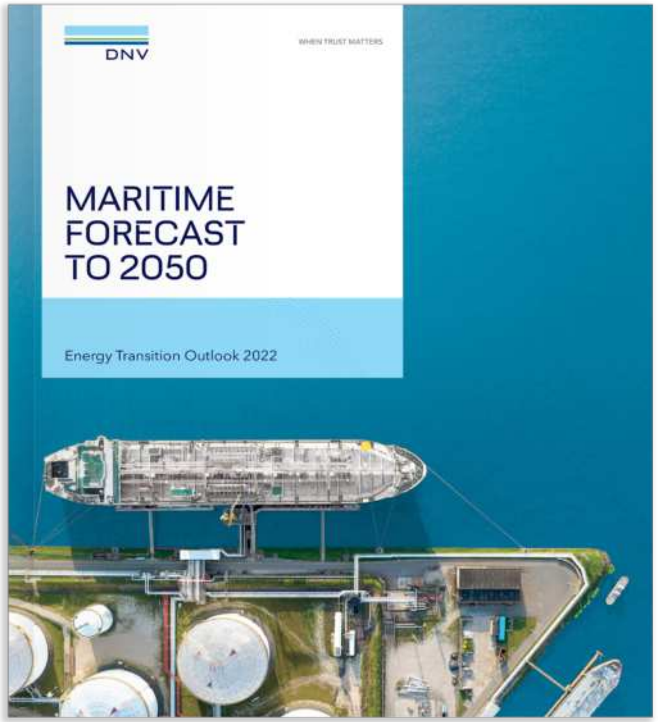
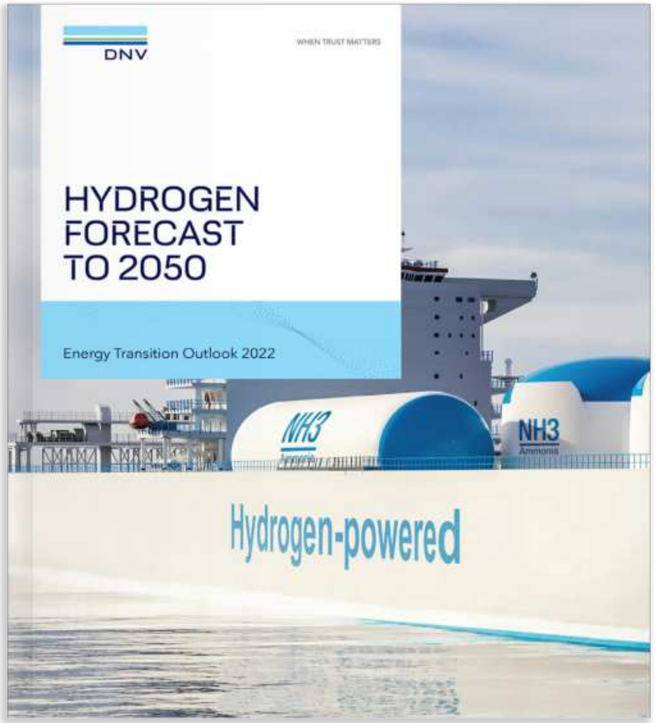
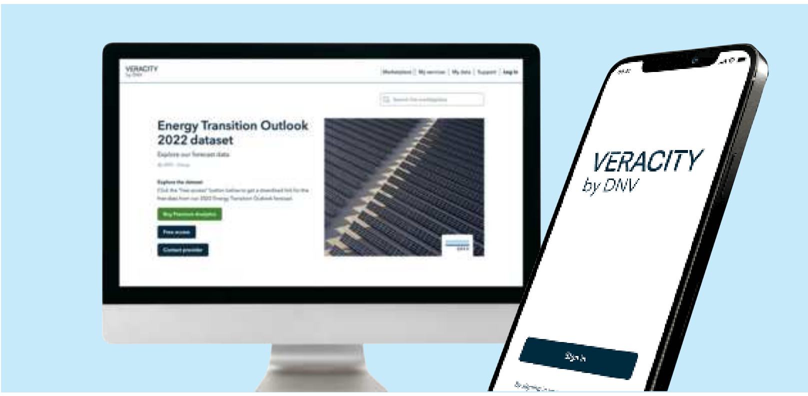


Maritime forecast to 2050
The 2022 *Maritime Forecast to 2050* presents an updated outlook on regulations, drivers, technologies and fuel availability. From that a new and extended fuel-mix scenario library has been created, with each scenario describing a possible future fleet composition, its energy use and fuel mix, and emissions to 2050. The library can be applied to DNV's updated Carbon-Risk-Framework and support shipowners in their decision making.



Hydrogen forecast to 2050
DNV's new report on hydrogen supply and demand and its role in decarbonization. The report details, inter alia, policy driving the rise of hydrogen ecosystems, developments in approaches to safety, technical aspects of production, storage and transport of hydrogen, expected developments in the regional and international trade of hydrogen and its derivatives, and a comparison of various hydrogen value chains.



Download our forecast data

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

eto.dnv.com/forecast-data

PROJECT TEAM

This report has been prepared by DNV as a cross-disciplinary exercise between the DNV Group and our business areas of Energy Systems and Maritime across 20 countries. The core model development and research have been conducted by a dedicated team in our Energy Transition Outlook research unit, part of the Group Technology and Research division, based in Oslo, Norway. In addition, we have been assisted by external energy transition experts, with the core names listed below.

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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 2022, 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 2021) numerical data is mainly based on IEA data from World Energy Balances© OECD/ IEA 2022, www.iea.org/statistics, License: www.iea. org/t&c; as modified by DNV.

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