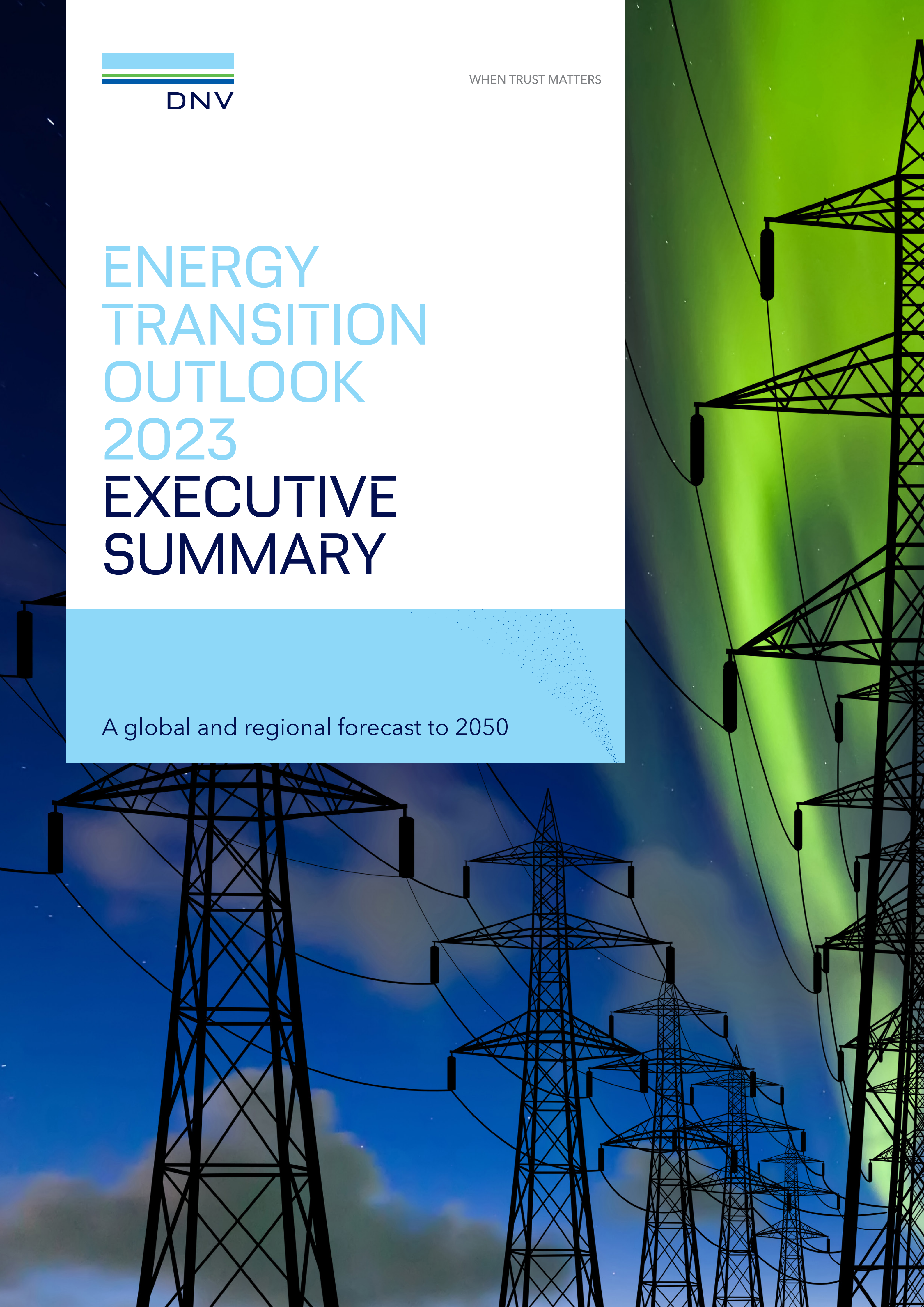
DNV

WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK 2023 EXECUTIVE SUMMARY

A global and regional forecast to 2050



FOREWORD

If 'energy transition' means clean energy replaces fossil energy in absolute terms, then the transition has not truly started.

The transition has happened in some regions and for many communities and individuals, but globally, record emissions from fossil energy are on course to move even higher next year. Up to the present, renewables have met some, but not all, of the world's additional energy demand. Optically, the transition seems to be in stall mode, with high oil and gas prices fuelling an exploration surge while many renewable projects are experiencing an increase in cost due to inflationary and supply-chain pressures.

So, when will the real global transition begin? Our prediction is that emissions from oil use will peak in 2025 and those from natural gas in 2027. EV uptake and solar PV installations, both of which are now at record levels, are set to continue strongly. Moreover, the *Fit for 55* and *RePowerEU* policies in the EU and the *Inflation Reduction Act* in the US are already demonstrating powerfully that decarbonization policies can work on a grand scale. In our forecast, non-fossil sources constitute 52% of the energy mix in 2050, a sharp increase from the 20% they represent today.

We have frequently used numbers to place a dimension on two corners of the energy trilemma: affordability (such as levelized cost and prices) and sustainability (such as carbon emissions intensity). So far, the third corner of the trilemma – energy security – has been largely viewed in a qualitative way. In the past 18 months the world has experienced the consequences of the 'grab for gas' in the wake of Russia's invasion of Ukraine and the reversion to coal in some regions as a cheaper alternative to gas. We have also seen increased attention to renewable projects in most places, as domestically-sourced energy is harder to disrupt and many governments are looking at nuclear with renewed interest.

Local sourcing of both energy and energy infrastructure is emerging as a prominent national objective. This year, our research team has revised our power sector forecast to better reflect the existing and future willingness of countries to pay a premium for locally-sourced energy – and that has notably impacted our results. For example, for the Indian Subcontinent we now forecast a slower transition with more coal in the energy mix, and in Europe the transition is accelerating with the alignment of climate, industrial, and energy security objectives.

Short-term energy forecasting has been a thankless task in the recent context of the pandemic, war, and price shocks. However, within our system-dynamics approach, the long lines of development are clear: the energy landscape will look very different in the space of a single generation. We forecast a 13-fold increase in solar and wind electricity production by mid-century. Electrification will more than double between now and 2050, bringing efficiencies to the energy system, which, as we detail in this report, brings down the cost per unit of energy for consumers in the longer run. However, in the coming ten years, a critical issue is how quickly that can happen with a lack of electric grids and renewable supply-chain capacity emerging as critical bottlenecks to a faster transition. And a faster transition is most definitely needed because our 'most likely' forecast for our energy future through to 2050 translates into global warming of 2.2°C by the end of this century.

Achieving a net-zero energy system by 2050 to secure a 1.5°C warming future is more difficult than ever. That does not mean we should not be aiming for that target. With more expansive policies promoting renewable electricity and other zero-carbon solutions, not just in the high-income world, but globally, we have the means to keep the world on track to be at, or very near, net zero by mid-century.

Remi Eriksen

Group president and CEO

DNV

HIGHLIGHTS

The transition is still in the starting blocks

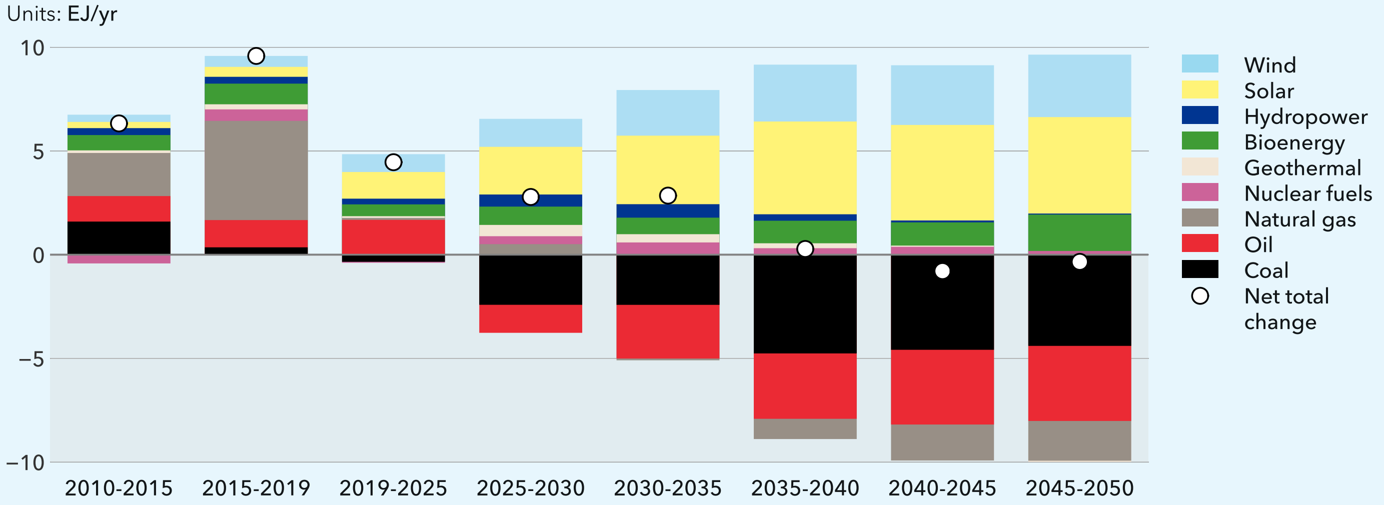
- Global energy-related emissions are still climbing and are only likely to peak in 2024. That is effectively the point at which the transition begins, even though across many nations and communities, energy-related emissions have already started to fall
- Over the last five years (2017–2022) renewables have met 51% of new energy demand and fossil sources 49%. In absolute terms, fossil-fuel use is still growing
- The 'grab for gas' in the wake of Russia's invasion of Ukraine, and the disruption of the oil market, has led to high prices and a surge in new oil and gas projects.
- High gas prices have also seen several countries intensify coal-fired power generation over the last 18 months, driving emissions yet higher. Natural gas is losing its status as a 'bridging fuel' for the transition

Renewables outsprint fossils from the mid-2020s

- The transition involves both the addition of renewables *and* the removal of fossil sources (Figure 1)
- It will take the next 27 years to move the energy mix from the present 80% fossil 20% non-fossil split to a 48%:52% ratio by mid-century
- From 2025 onwards, almost all net new capacity added is non-fossil. Wind and solar grow ten-fold and 17-fold, respectively, between 2022 and 2050
- Over the next decade, new fossil production in low- and medium-income countries will largely be nullified by reductions in high-income countries
- Coal use peaked in 2014 but has come close to that level in recent years. However, its share of primary energy falls from 26% today to 10% in 2050
- Fossil primary energy demand declines from 490 EJ to 314 EJ by 2050. Cumulatively, the fossil energy *not* used compared with today's use amounts to 1,673 EJ or 275,000 million barrels of oil equivalent by 2050

FIGURE 1

Net change in primary energy supply by source



Net change of primary energy between 5-year intervals. 2019 used to avoid effect of COVID-19. Historical data source: IEA WEB (2023)

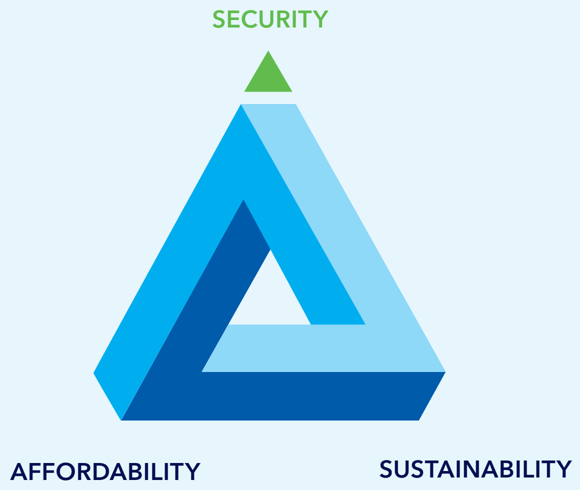
HIGHLIGHTS

Energy security is moving to the top of the agenda

- Geopolitical developments over the last 18 months have brought energy security into sharp focus with the disruption of energy supplies and price shocks for energy importers
- Worldwide, energy produced locally is being prioritized over energy imports
- This trend is favouring renewables and nuclear energy in all regions and coal in some regions
- We have now factored into our power sector forecast the willingness of governments to pay a premium of between 6% and 15% for locally-sourced energy
- Reshoring and friend-shoring policies are adding to supply chain complexities and costs already strained by inflation
- 2022 saw an increase in the levelized cost of renewables in several regions, particularly with wind projects, but we expect cost reductions to return to historic learning curve rates by 2028
- In the long term, energy security and sustainability will pull in the same direction, with decarbonizing energy mixes – with wind, solar, and batteries as the main sources – increasingly shielding national energy systems from the volatility of the international energy trade

FIGURE 2

Energy trilemma



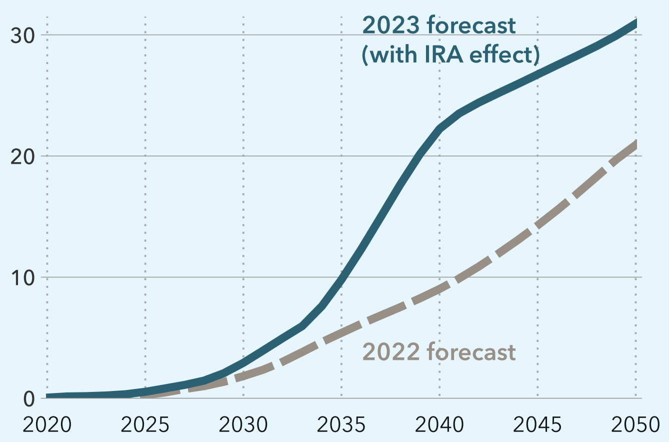
Progressive policy is making an impact

- Big decarbonization policy packages rolled out in the last year are supercharging the transition regionally and nudging it forward globally
- *The Inflation Reduction Act* is accelerating the transition in the US, with USD 240bn already committed in clean investments in response to the broad array of incentives under the Act
- In the EU, the *EU Green Deal*, *REPowerEU*, and *Fit for 55* policy packages make Europe's net-zero goal more realistic
- Shipping is set for a faster transition due to the inclusion in EU's emission trading system and the IMO's ambitious new decarbonization strategy aiming for net zero by 2050
- The 'race to the top' in clean technology amongst the advanced economies will drive global learning benefits in e.g. hydrogen and carbon capture and storage technologies
- The scaling of clean tech in advanced economies will only partly benefit medium- and low-income regions where economic development and other SDGs are prioritized. De-risked financing is needed to accelerate the pace of the transition beyond leading regions

FIGURE 3

Hydrogen production in North America

Units: MtH_2/yr



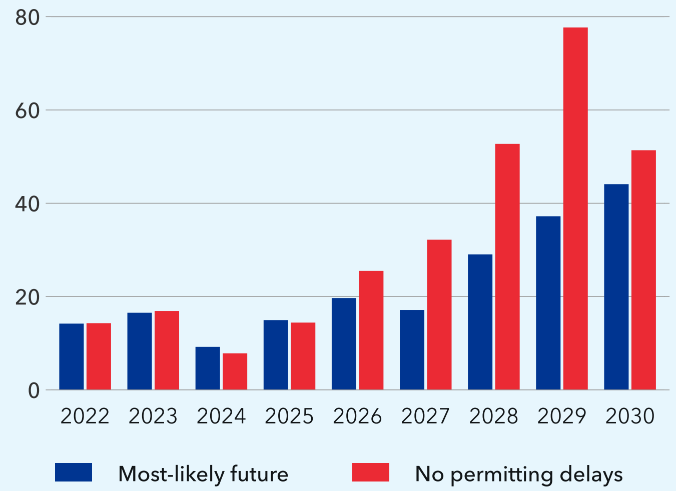
Gridlock impeding the near-term expansion of decarbonization technologies

- Despite inflationary and supply-chain headwinds, solar installations reached a record 250 GW in 2022. Wind power contributed 7% of global grid-connected electricity and installed capacity will double by 2030
- The global grid – transmission and distribution combined – will double in length from 100 million circuit-km (c-km) in 2022 to 205 million c-km in 2050 to facilitate the fast and efficient transfer of electricity. However, in the near term, transmission and distribution grid constraints are emerging as the key bottleneck for renewable electricity expansion and related distributed energy assets such as grid-connected storage and EV charging points in many regions, including the US, Canada, and Europe
- Our forecast factors in the impact of lagging grid capacity in the near- and medium-term to build-out rates of renewables
- Both the EU and the US are advancing policies to address permitting delays, but a deeper policy response is needed, which may encompass expropriation and financing to ease cable manufacturing production constraints
- Grid expansion is important for the production of hydrogen, which in turn is dependent on more robust demand-side measure to incentivize offtake

FIGURE 4

Global offshore wind capacity additions with and without permitting delays

Units: GW/yr



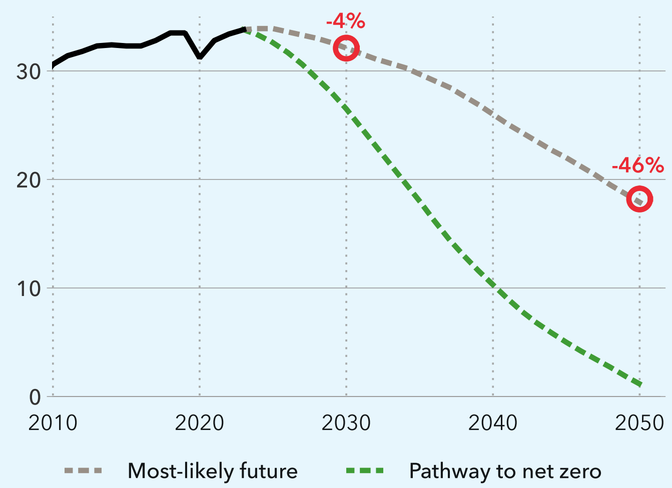
Global emissions will fall, but not fast or far enough

- We forecast global energy-related CO_2 emissions in 2050 to be 46% lower than today, and by 2030, emissions are only 4% lower than they are today
- The emissions we forecast are associated with 2.2°C of global warming above pre-industrial levels by the end of this century
- From 2024, the share of renewables in the primary energy mix will grow by more than one percentage-point per year, resulting in a 52% non-fossil share by 2050, up from 20% today
- The pace of the transition is far from fast enough for a net-zero energy system by 2050. That would require roughly halving global emissions by 2030, but our forecast suggests that ambition will not even be achieved by 2050
- Limiting global warming to 1.5°C is therefore less likely than ever
- While emissions rise, the consequences of climate change are becoming more visible and impactful, with extreme weather events becoming more frequent and damaging

FIGURE 5

World energy-related CO_2 emissions, after DAC

Units: $GtCO_2$/yr



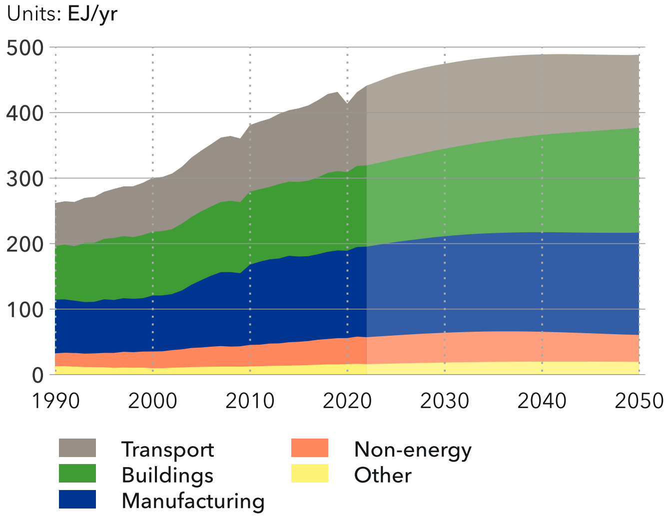
DEMAND

By 2050, we expect the global population to increase by about 20% to some 9.6 billion people and the global economy to almost double to USD 320trn. A more prosperous and populated world will be using some 90% more energy services (e.g. goods produced, kilometres of transport, and square metres heated) compared with today.

The energy delivered to the key demand sectors – transport, manufacturing, and buildings – is termed 'final energy demand' and includes both useful energy (essentially the aforementioned energy services) *and* wasted energy. For instance, most of the energy – the gasoline – delivered to an internal combustion vehicle is wasted mainly as heat, and just 25% to 35% is used to propel the vehicle.

FIGURE 6

World final energy demand by sector



Historical data source: IEA WEB (2023)

By 2050, the world's energy system will be greatly more electrified than today and hence very much more efficient. Consumers will be doing a lot more with the energy delivered to them. Thus, while energy services will roughly double through to mid-century, final energy demand will grow by only 10%, from 441 exajoules (EJ) to 489 EJ. Figure 6 shows that most of this growth occurs in the years to 2040, after which final energy demand levels off through to 2050.

Manufacturing

Despite substantial efficiency gains and increased recycling, final energy demand for manufacturing will keep growing at some 0.5% per year to reach 156 EJ by mid-century – keeping its share of global final energy demand steady at 30% throughout our forecast period. Fossil sources dominate the manufacturing energy mix today but will steadily be displaced by direct electrification, hydrogen, and bioenergy. Coal will remain the largest energy carrier, however, driven by persistent use in Greater China and the Indian Subcontinent.

Energy demand for manufactured goods will rise by 46%. Electricity use will roughly double and is the primary reason for fossil fuels shrinking from supplying half the energy for manufactured goods today to about one third in 2050. The Indian Subcontinent will take over from Greater China's leading position and will account for more than a third of the subsector's energy demand by 2050.

Steel production will grow by 15%, but because Electric Arc Furnace method's share in global steel production rises from 26% today to 49% in 2050, energy demand for steelmaking will peak in 2030. Coal will still meet half the subsector's energy demand by mid-century.

Energy demand for chemicals and petrochemicals will grow by about 20% by the mid-2030s but then decline progressively after that, mainly due to increasingly higher rates of plastic recycling towards 2050.

The base materials subsector includes the production of non-metallic minerals, excluding cement; non-ferrous materials, including aluminium; and wood and its products, including paper and pulp. Here, energy demand will rise by one sixth, but energy demand is dampened by the decarbonization of the fuel mix and 33% increase in the use of electricity.

Factoring energy security and geopolitics into our forecast

A high focus on energy security, increasing protectionism and attendant changes in supply chains, and other developments in the geopolitical landscape have a direct impact on the global and regional energy transitions. We reflect this in the 2023 ETO model and results.

- We have factored into our power sector forecast the willingness for governments to pay a premium of 6% to 15% for locally-sourced energy such as renewables, nuclear, and coal, with significant regional variations given import/export dependencies and types of local resouces
- We are moderately changing manufacturing volumes in our model, where manufacturing sector output is reduced in some regions and diverted to other regions, to reflect reduced dependence on a single manufacturing hub and efforts to boost supply chain resilience
- We have factored into our model a modest cost increase of up to 10% in the medium term for solar, wind, and battery technolgies in some regions to cater for reshoring energy technology manufacturing, which drives costs somewhat higher

The overall effect on the ETO 2023 results is clearly visible for the first of the factors listed above. The impact of the other two factors is relatively small. We will continue to carefully monitor these trends to understand more about their impacts on the energy transition and how to model those in our forecast.

We discuss our thinking on energy security and geopolitics in greater detail in the main ETO report.

Cement production is expected to grow less than 20% but its energy mix will remain highly carbon intensive, with electricity and hydrogen playing only marginal roles. Decarbonization goals will rely on CCS.

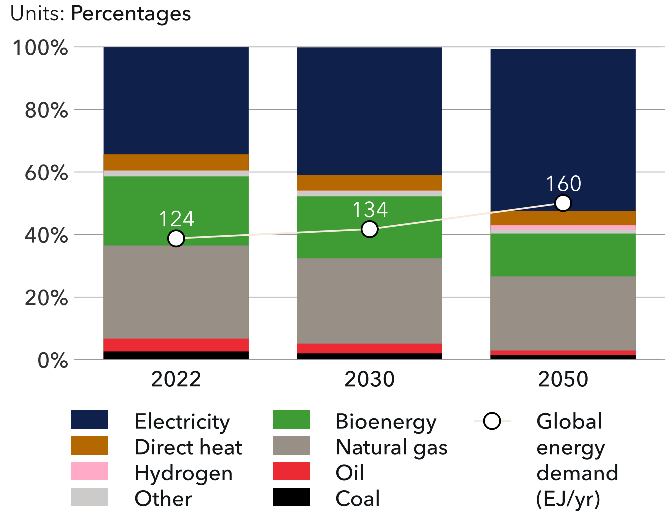
Construction and mining will see the highest relative increase in energy demand (50%), but almost all of that growth will be met by an expansion of electrification.

Buildings

Global energy demand for buildings is set to grow nearly 30%, from 125 EJ per year in 2022 to 161 EJ per year in 2050. This one-third growth in energy demand should be weighed against the fact that there will be a 58% expansion of combined residential and commercial floor area. Energy demand will be dampened by increased electrification and improvements in the efficiency of thermal insulation and heating/cooling equipment. Even so, the buildings sector will displace transport as the demand

FIGURE 7

Buildings energy demand by carrier



Historical data source: IEA WEB (2023)

sector with the largest share (33%) of the total final energy demand in 2050.

The growing prominence of electricity in the buildings energy mix, increasing from 34% in 2022 to 52% in 2050, results in decreased dependency on gas (declining from 30% in 2022 to 24% in 2050) and biomass (currently at 24%, expected to drop to 14% in 2050). Additionally, by 2050, heat pumps, achieving up to 300% efficiency, will provide 32% of the total useful energy for space heating and 22% for water heating, while consuming only 13% and 5% of final energy, respectively. As a result, energy demand for space heating will fall by over 10%.

The growing energy demand for lighting and appliances (60% from now to 2050) is only partly offset by energy intensity improvements (0.6%/yr).

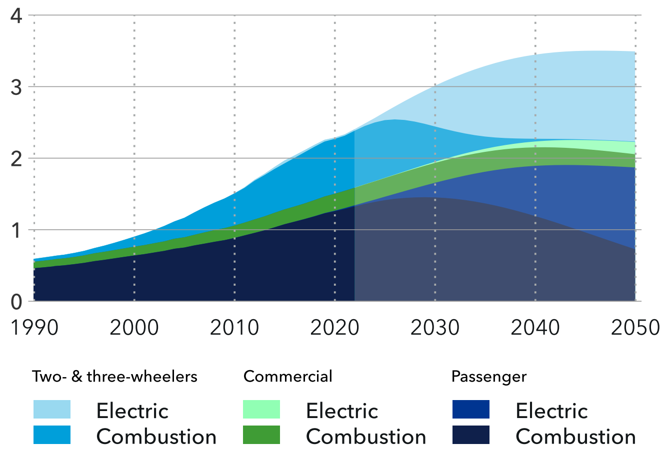
The demand for space cooling will be amplified by global warming and increasing incomes per capita, and it quadruples by mid-century to take a 17% share of buildings energy demand.

Feedstock
Oil and natural gas dominate today's fuel mix for feedstock, or 'non-energy' use, meeting 54% and 42%, respectively, of demand in 2022, with coal covering the rest of the mix. Feedstock demand for natural gas remains stable at

FIGURE 8

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 (2023), EV Volumes (2022)

the current level of 18 EJ, while non-energy oil demand rises from some 22 EJ to peak at 26 EJ in mid-2030s before returning to today's level by 2050.

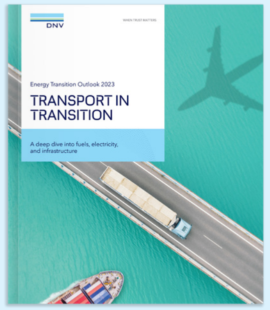
Demand increases are driven initially by plastics and bitumen, outpacing a decline in lubricants in road transport. However, ever-higher plastic-recycling rates, due to regulations and technology advances, will see demand for virgin resin fall from the mid-2030s, even as plastic end-use demand rises from 450 Mt per year in 2020 to 860 Mt per year in 2050.

Transport
Between now and 2050 there will be a near-doubling in the size of the vehicle fleet: passenger flights will grow 140%, cargo tonne-miles at sea will expand by 40%, and rail energy demand will almost double while passenger numbers more than double. In 2022, all these transport activities consumed 121 EJ. Yet, in the much busier world of 2050, transport activities will in fact consume 9% less energy than at present, or 111 EJ. Between 2022 and 2050 there will be a 46% fall in the use of oil for transport (-50 EJ), owing to electrification and consequently increased efficiencies in road transport.

Efficiency gains in the road-transport subsector will more than counterbalance growth in energy demand in aviation, but fortunately, an increased share of biofuels, hydrogen, and its derivatives in aviation, as well as maritime transport, will also contribute to total transport-related emissions falling 44% by mid-century.

Road transport: The world's vehicle fleet (passenger, commercial and two- and three-wheelers) expands from 2.4 billion to 3.5 billion vehicles from 2022 to 2050. From 2040, this fleet size will start plateauing owing to the effects of automation and saturation. We forecast that EVs will comprise 50% of the new passenger vehicle market share in Greater China and Europe by the late 2020s, in OECD Pacific and North America by the early 2030s, and globally by 2031. We project a swift electrification of two- and three-wheelers; already, more than a third of all two- and three-wheelers sold in China are battery powered. The electrification of commercial vehicles will take place at a slower pace than for passenger vehicles, with the 50% share of new sales by EVs occurring in the late 2030s.

Even though EVs are predicted to constitute almost three-quarters (72%) of the global vehicle fleet by 2050,



TRANSPORT IN TRANSITION
See article on DHL Express – a front-runner with SAF, on page 53 in our *Transport in Transition* report.
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Image, courtesy: Deutsche Post DHL

they will only contribute around 30% of the energy demand within the road subsector, while hydrogen-powered FCEVs will contribute an additional 5%. The smaller segment of the vehicle fleet still reliant on fossil-fuel combustion will be responsible for the major portion of energy consumption. In 2050, oil will account for nearly 60% of the global road subsector's energy demand, with natural gas representing 4%.

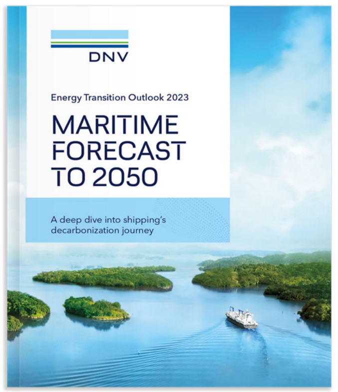
Aviation: With strong demand growth in Greater China and South East Asia, passenger trips per year are likely to rise 140% above pre-pandemic levels by 2050, despite a re-basing of business travel 20% below our pre-pandemic forecast. Efficiency gains in engines, aircraft technology, and logistics will 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 12% of the energy mix. That leaves oil still dominant by 2050, 21% higher 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 2023 updated IMO GHG strategy encompasses new levels of ambition, such as aiming to achieve net-zero emissions by approximately 2050. We expect this to be not fully met despite a mixture of improved fleet and ship utilization, wind assisted propulsion, onboard CCS, energy efficiency improvements, and a massive fuel switch. However, we forecast a more decarbonized fuel mix than a year ago.

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 40% between 2022 and 2050. Important shifts include coal transport reducing a fourth by 2050 in tonnes, crude oil tanker increasing global tonne-miles travelled by a fourth, while oil products transport reducing by 25%.

From being almost entirely oil-based today, the 2050 fuel mix is 84% low- or zero-carbon fuels and 8% natural gas (mostly LNG). Ammonia has 36% of low- and zero-carbon fuels share, e-fuels 19%, and biomass some 25%. Potential for electrification in the maritime sector is limited and thus electricity will have only 4%. See DNV's *Maritime Forecast to 2050* for details.



Our *Maritime Forecast to 2050* provides valuable insights to empower information-based decision making for all maritime stakeholders on their decarbonization journey.

ENERGY EFFICIENCY

The Sankey diagrams (opposite) compare global 'final' energy demand to 'useful energy' in 2022 and 2050. 'Final energy' is what is directly delivered to end-users in forms such as oil, gas, electricity, or hydrogen before that energy is converted to energy services or 'useful energy' with associated losses.

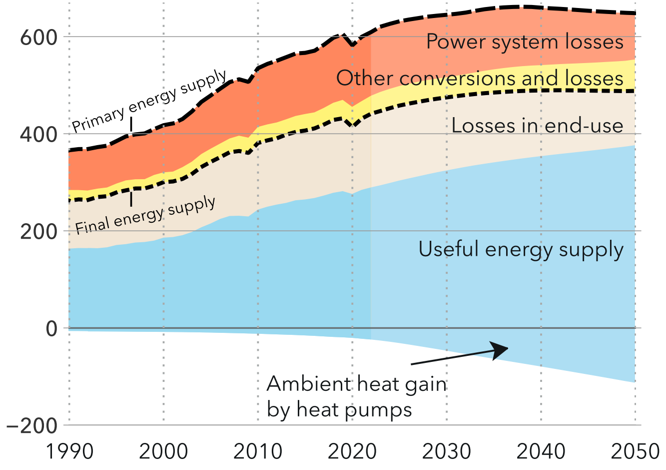
Between 2022 and 2050, we project a 90% increase in global useful energy demand from 314 EJ/yr to 494 EJ/yr. In the same period, final energy demand is expected to grow by only 10% to 489 EJ/yr. This difference is startling and historically unprecedented.

Our observations highlight inherent inefficiencies in many energy-consuming systems today, e.g. the internal combustion engine. Its tank-to-wheel efficiency typically lies between 25% and 35%. Combustion equipment like boilers, burners, furnaces, and stoves, especially those fuelled by fossil fuels, reflect a similar story, with about one-third of the energy in fuels remaining unused on a global scale. By 2050, the average efficiency of combustion equipment will only increase to around 70% despite potential technological shifts such as the adoption of gas for cooking instead of solid biomass.

FIGURE 9

Losses in the global energy system

Units: EJ/yr



Historical data source for primary and final energy: IEA WEB (2023)

In contrast, electrical equipment like electric motors and heaters consistently demonstrate high efficiencies, many above the 90% mark. Heat pumps even 'amplify' the input final energy into a greater output of useful energy by extracting ambient environmental energy. The push for electrification is effectively the push for efficiency.

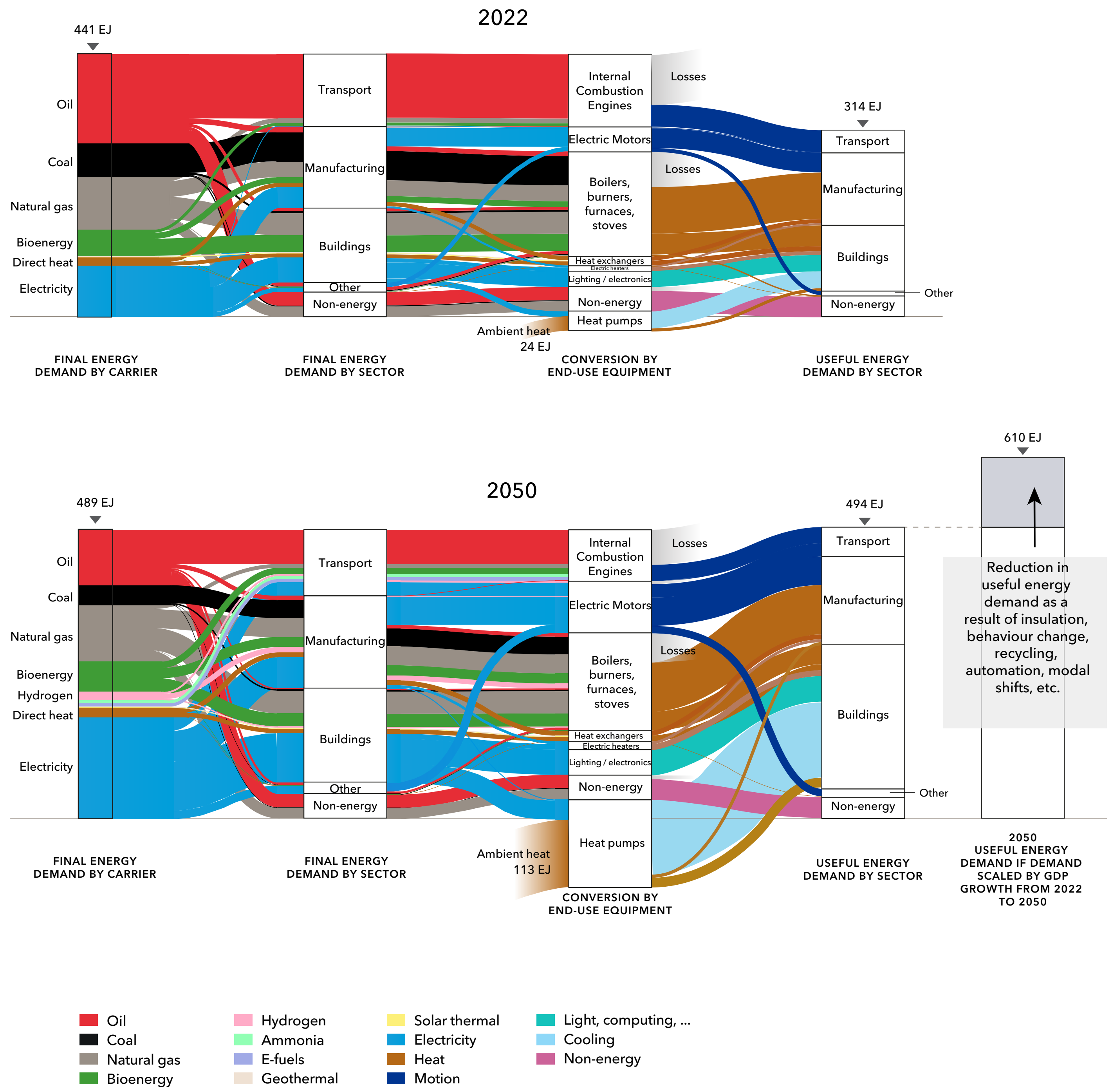
By 2050, the heat extracted by heat pumps will effectively offset the cumulative losses witnessed in internal combustion engines, boilers, heaters, furnaces, and stoves. As a result, the total useful energy supply is projected to marginally surpass total final energy. Very different from the situation in 2022, when the global useful energy constituted a mere 72% of the final energy supply.

Strategies aimed at reducing the demand for energy services – e.g. insulating buildings, recycling, or congestion charges on vehicles – play a significant role in our predictions. These strategies may not directly improve the ratio of final to useful energy, but potentially curb or even negate useful energy consumption. By comparing the useful energy demand we project for 2050 with a hypothetical demand that would scale linearly with global GDP, we estimate that these strategies will reduce the energy demand by about 118 EJ/yr (19%) from an expected 610 EJ/yr (Figure 10).

Figure 9 charts the evolution of loss sources in the global energy system. Power generation, encompassing electricity and direct heat, is the chief contributor of loss between primary and final energy. Other losses emerge from conversions like hydrogen production and the energy system's consumption, termed 'energy sector own use', and are not included in final energy demand. As renewables dominate by 2050, power system efficiency will rise to 70% in 2050 from 44% in 2022. Even with the doubling of electricity and direct heat demand from 2022 to 2050, power generation losses remain constant.

FIGURE 10

Flow of global final to useful energy demand through conversions by end-use equipment in 2022 and 2050



Historical data source for final energy: IEA WEB (2023), useful energy: DNV's own estimates

ENERGY SUPPLY

Global primary energy supply will reach its maximum in 2038 at 663 EJ per year, 9% higher than today, before reducing to 656 EJ in 2050. This is because conversion losses reduce considerably as the share of non-fossil energy increases. The fossil share will fall from 80% today to 48% in mid-century. The decline is quickest for coal, going from 26% to 10% over the next 27 years, followed by oil, which falls from 29% to 17% over the same period. The natural gas share remains almost static throughout.

The share taken by nuclear energy will increase slowly over the forecast period, ending at 6% in 2050, while the renewables share will triple from 15% today to 46% by the end of the forecast period. Within renewables, the large increase will be driven by solar and wind, which will see 17-fold and 10-fold increases in primary energy supply towards 2050, respectively. Solar will reach 17% and wind 11% of the global primary energy mix in 2050, with further growth expected beyond mid-century. Bioenergy and hydropower will also grow, in both relative and absolute terms.

Coal – use declines by two thirds

After peaking in 2014 at 8 Gt, coal use was on a downward trajectory globally, but saw a considerable bounce-back in 2022 to near record levels. This was due to a confluence of factors: the reactivation of coal plants in Europe in response to the energy crisis caused by Russia's war on Ukraine; in China high gas price and drought affecting hydropower output led to a surge in coal-fired power; and rising coal use in India and South East Asian countries. However, coal use will decline by two thirds by mid-century – falling by 90% and 80% in North America and Europe, respectively. Greater China, currently the largest coal consumer, will witness a 70% reduction in coal use, primarily due to declining steel production (down 65%). In contrast, the Indian Subcontinent will see a doubling of coal demand for iron and steelmaking, nearly matching Greater China's demand by mid-century.

Oil – use falls 38%

Oil currently holds the largest share (29%) of primary energy but is expected to fall to 17% by 2050, with demand then at 52 mbpd, roughly 40% lower than its peak this decade. Despite record EV sales and the ongoing build-out of non-fossil electricity generation capacity, global oil demand is expected to increase by between 3% and 4% over the next three years before levelling off and then starting to decline before 2030. As electrification in road transport accelerates, the decline between 2035 to 2050 is almost twice that seen over the period 2025 to 2035. Overall oil use in transport will halve over our forecast period. Oil use will persist in some subsectors, for example aviation, where its use will match the offtake from road transport by mid-century. With declining oil use for most energy purposes, the share of non-energy use in oil demand rises from 13% today to 22% in 2050. Production will be concentrated ever more strongly in the Middle East and North Africa.

Natural gas – staying power but 10% lower in 2050

Natural gas peaks in 2036 and slowly tapers off to end some 10% below today's levels. It surpasses oil as the world's leading energy source by the mid-2030s. Demand increases to around 5,000 billion m^3 (175 EJ) around 2027, and plateaus for about a decade before declining to 4,200 billion m^3 in 2050.

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 towards the end of 2030s, and tripling in the Indian Subcontinent by 2050.

Gas transport capacity, LNG or pipelines, is set to rise despite stable global gas demand, due to a shift in demand patterns to regions with little pipeline import, and a heightened focus on energy security and diversity of supply. The Middle East and North Africa region has the largest installed liquefaction capacity today. However, North America – being distant from its natural gas export customers – will increase its liquefaction capacity by 37% to reach the same level as in the Middle East and North Africa in 2030.

By mid-century, just 6% 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.

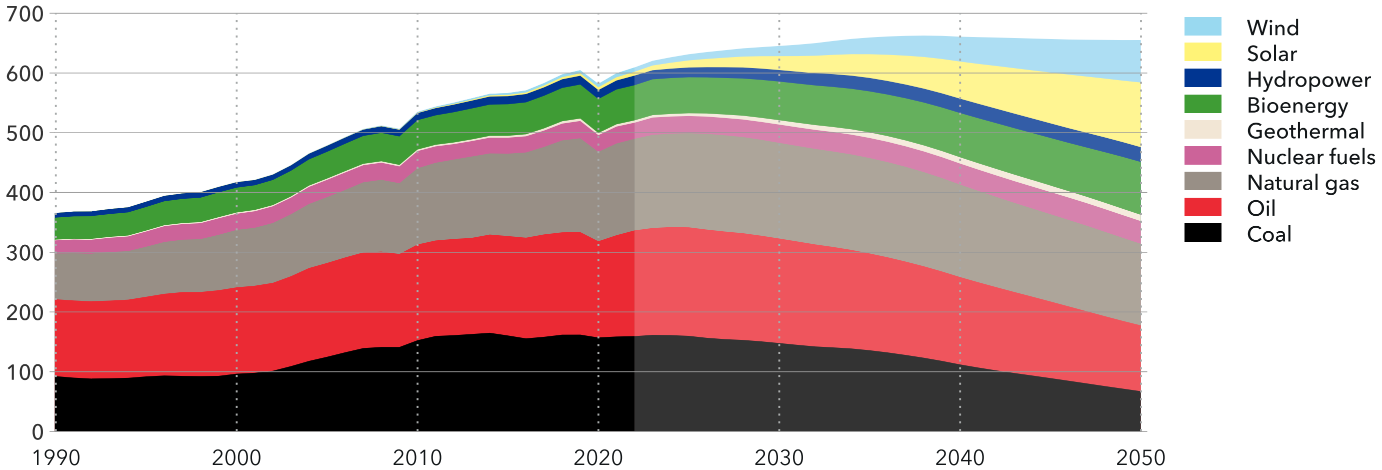
Nuclear – boosted by energy security concerns

Our Outlook this year reflects the renewed interest in nuclear energy sparked by energy security concerns. Our forecast shows nuclear energy output growing from the late 2020s, with most added capacity before the early 2030s being site-built, large-scale reactors already in the pipeline. Output growth then picks up with additional capacity added as a mix between site-built and factory-manufactured SMR power plants. Output peaks at 3,500

FIGURE 11

World primary energy supply by source

Units: EJ/yr

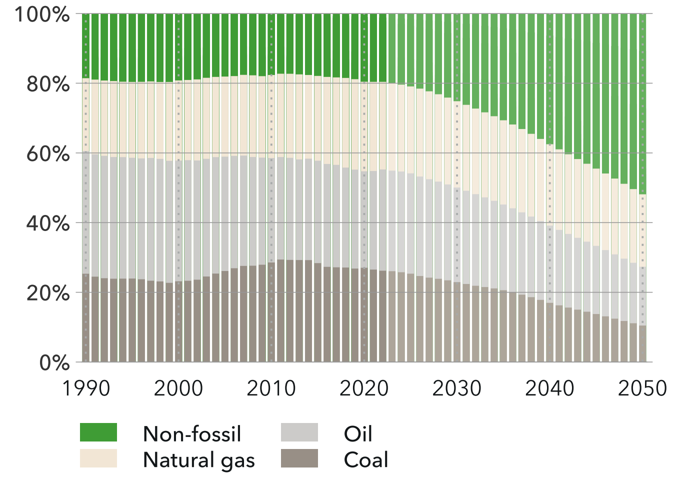


Historical data source: IEA WEB (2023)

FIGURE 12

Fossil vs. non-fossil in primary energy supply

Units: Percentages

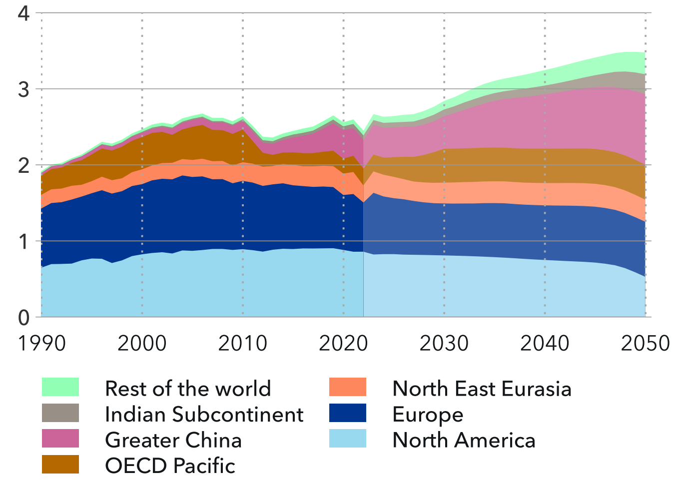


Historical data source: IEA WEB (2023)

FIGURE 13

Nuclear power generation by region

Units: PWh/yr



Historical data source: IEA WEB (2023)

TWh per year by 2047, a level 41% higher than today. Energy security concerns are likely to prompt governments pay a premium ranging from 8% to 20% of the levelized cost of nuclear energy, from 2023 to 2050. This has the effect of adding 5% more capacity that would have been the case without such concerns, although there is uncertainty in this figure given that renewables are often a better means of addressing energy security. While SMR technology shows promise, it is a decade away from any commercial scale. In addition, SMRs potentially involve an order of magnitude more sites, in more countries, which could negatively impact safety, waste management, and proliferation risks.

Solar – a 13-fold growth

Solar installations have risen from 1 GW in 2004 to 250 GW by 2022. By 2040, global installations are projected to reach 500 GW annually. By 2050, we will see solar PV capacities of 8.8 TW and an additional 6.5 TW for solar+storage, bringing the total to 15.3 TW, a 13-fold growth from 2022. By mid-century, solar will represent 54% of global generation capacity but only account for 39% of on-grid electricity due to low capacity factors. Cost reductions are the main driver of solar's proliferation, with the levelized cost of energy (LCOE) expected to drop to an average around USD 21/MWh by 2050 from their present level of USD 41/MWh. Concurrently, unit investment costs are forecast to decrease to USD 560/kW by 2050. Despite the expected slowdown in the learning rate for solar module costs, solar PV will be the most cost-effective electricity source globally.

With higher market penetration, solar (alongside wind) can often meet or even surpass the power demand, pushing electricity prices to near zero or even negative values. That is what makes storage systems, despite the added CAPEX, critical in supporting solar growth during sunless hours. Within a decade, 10% of all new PV will integrate dedicated storage, and by 2050, that number will ascend to 62%. Regional growth indicates dominance by Greater China and North America, while the Indian Subcontinent and the Middle East and North Africa will nearly triple their solar shares from 6% and 3% in 2022 to 14% and 12% by 2050, respectively.

By 2050, over 3 TW of off-grid solar will be dedicated to hydrogen production, mainly in Greater China (40%), Europe (26%), and North America (16%). A further 137 GW will be located in remote regions in Sub-Saharan Africa and the Indian Subcontinent, delivering life-changing electricity access for hundreds of millions of people.

Wind – a nine-fold growth

We forecast a nine-fold growth in grid-connected wind power generation globally, from 2,000 TWh in 2022 to 18,300 TWh by mid-century. That translates to a share of grid electricity rising from 7% in 2022 to 30% in 2050. Leading this growth are Europe, Greater China, and North America, where wind energy is a central pillar of national and regional energy policies.

Over the last year, the wind power sector has faced a perfect storm of challenges, including cost inflation, supply-chain disruptions, concerns about turbine and rotor quality, and shrinking profit margins for OEMs. As a result, we now predict a minor reduction in wind power generation and installed capacity by 2050 relative to last year's forecast, but our long-term projections remain optimistic due to rising capacity factors and steadily declining costs.

The global average capacity factor for onshore wind stood at 24% in 2022, but with advancements in digital control and rotor design, it is projected to rise to 30% by the 2030s and level off at 32% by 2050. For offshore turbines installed in 2022, capacity factors hover around 30%, but by mid-century it could be 42% to 43% and even exceed 50% in regions with optimal wind conditions. From a baseline of USD 49/MWh for projects in 2022, we anticipate the global weighted average LCOE for onshore wind to drop to USD 33/MWh by 2030. Costs decline more slowly after 2030 due mainly to a halt in rotor size advancement and the crowding of the most optimal sites. Our 2050 projection for onshore wind is thus USD 27/MWh. A steeper cost decline is expected for offshore fixed and offshore floating wind with respective LCOE currently at around USD 80/MWh and USD 270/MWh. Due to economies of scale and improved production efficiencies, the 2050 LCOE for offshore fixed wind is forecast at USD 51/MWh and floating offshore at approximately USD 67/MWh.

Hydropower – 50% growth

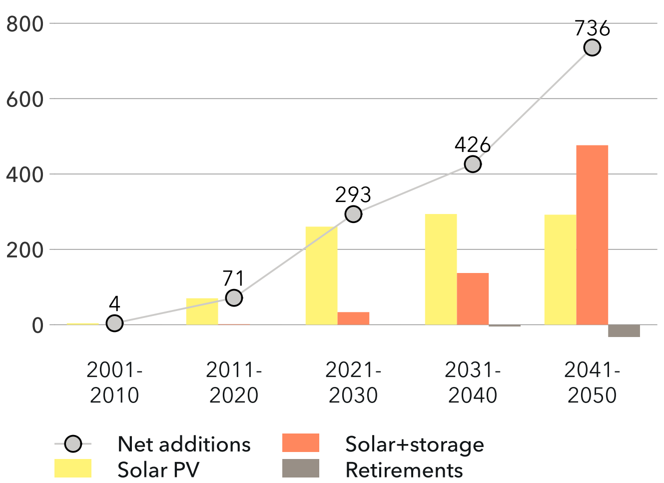
In 2022, hydropower was more than a third (37%) of total renewable energy generation, and more than a seventh (15%) of overall electricity generation. However, in contrast to solar PV and wind, hydropower growth towards 2050 will be moderate. Hydropower generation has doubled over the last 20 years, and growth will continue until it slows down and plateaus in 2040. Until then, most of the growth will be in Greater China, the Indian Subcontinent, and South East Asia. After 2040, growth in hydropower generation will stabilize in all regions. In 2050, such generation will provide little more than a tenth (11%) of the total electricity supply, down from 15% in 2022, although growth from today is more than half (54%) in absolute terms.

Bioenergy – doubling and critical for decarbonizing transport

The overall contribution of biomass to primary energy supply is expected to see a marginal increase, reaching approximately 11% by 2050, compared to the current 10%. The utilization of bioenergy in the transport sector will effectively double, mainly in the form of liquid biofuels, making these crucial for decarbonizing transport, particularly in aviation and maritime transport, where electrified propulsion technologies are less feasible.

FIGURE 14

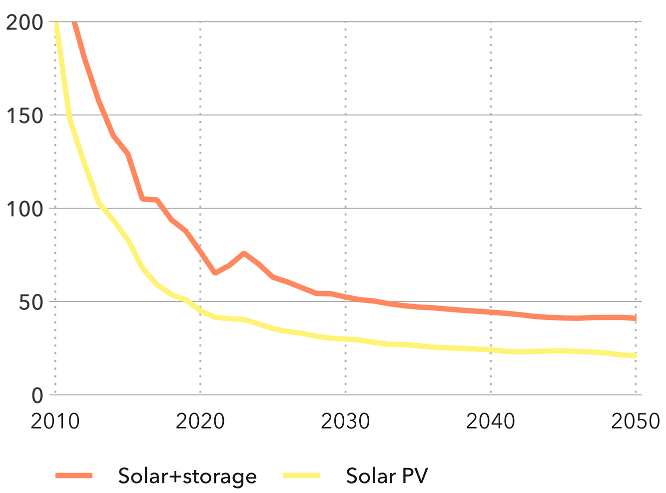
Global solar capacity additions and retirements, 10-year average



Historical data source: GlobalData (2023), IRENA (2023)

FIGURE 15

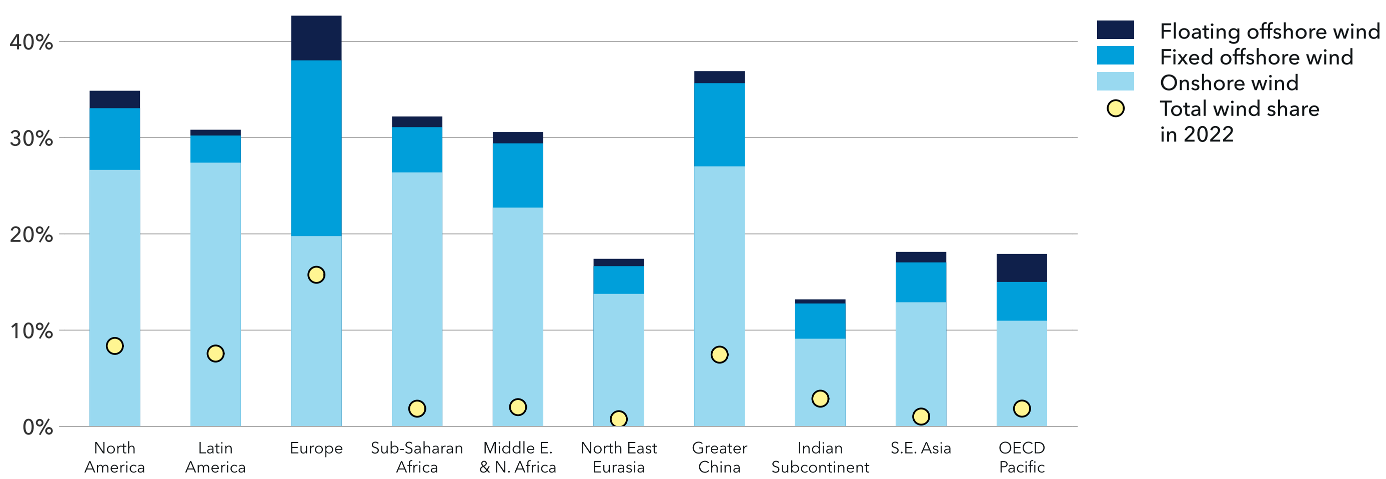
World average levelized cost of solar energy



Historical data source: GlobalData (2023), IRENA (2023), DNV analysis

FIGURE 16

Share of wind in electricity generation in 2050 by region



Historical data source: IEA WEB (2023) GlobalData (2023)

ELECTRICITY

The transition is characterized principally by a surge in electricity demand worldwide: it more than doubles from 29.5 petawatt-hours (PWh) demanded in 2022 to reach 60.8 PWh in 2050. Electricity will constitute 35% of the world's final energy demand in 2050, up from 19.5% in 2022.

Demand growth
This major expansion of electrification is driven by the burgeoning demand for existing applications as well as whole new categories of demand:

- **Transport** will account for a significant slice of the pie with 6 PWh/yr of the 31 PWh/yr spike in demand primarily due to the charging of an expected 2.6 billion EVs.
- In the **buildings sector**, global warming will contribute to the demand for space cooling rising by a factor of four, from 2.1 PWh to 7.6 PWh. The uptake of heat pumps for space and water heating will add a further 5.9 PWh of annual electricity demand by 2050.
- **Hydrogen production** via electrolysis will add several petawatt hours to the total demand.

As of 2022, Greater China leads global electricity consumption at 32%, and it is expected to maintain its top position by 2050, albeit with a reduced share of 26%. In contrast, the Indian Subcontinent is set to leapfrog both Europe and North America by 2050, commanding 14% of the global electricity share due to its fast-paced economic growth and burgeoning demand for cooling, appliances, and manufacturing services.

Generation
Electricity is not just growing but greening: in 2022, 31% of electricity generation came from renewables, and that share is projected to increase to 82% in 2050, of which about half will be generated by solar.

From its 2022 baseline of 8.8 PWh/yr, renewable electricity generation worldwide is set to expand by 23.8 PWh/yr by 2035. Yet, an increase in demand by 13.6 PWh/yr during the same period means that it is only from the early 2030s that renewables start to genuinely replace fossil fuels in power generation. We caution that there are strong regional variations in the electricity mix, with regions such as the Middle East and North Africa, the Indian Subcontinent, and North East Eurasia remaining strongly dependent on fossil-fired power generation due to a combination of financial constraints and under-developed renewable infrastructure.

Our analysis of average LCOE is summarized as follows:

- **Solar PV** USD 30/MWh by 2030 declining to USD 22/MWh by 2050, with on-site storage adding roughly another USD 20/MWh to the levelized cost.
- **Onshore wind** LCOE lags solar PV by five years in reaching USD 30/MWh and is USD 27/MWh by 2050.
- **Fixed offshore wind** LCOE is around USD 68/MWh by 2030, reducing to the USD 51/MWh mark on average in 2050, but will be as low as USD 32/MWh in ideal locations. Once established, floating offshore wind maintains a USD 16/MWh LCOE premium over fixed offshore wind.

With some differences in timing, the global LCOE averages for natural gas, hydropower and nuclear trend from roughly USD 100/MWh in 2030 to somewhere above the USD 60/MWh range by mid-century – in other words, substantially above solar PV and almost all wind generation. Coal-fired power stations have an upward LCOE trend towards the USD 100/MWh level due to declining capacity factors. The persistence of these conventional sources in the power mix, however, also needs to be considered in the context of revenue-adjusted LCOE, which accounts for the difference between a technology's earnings and the market's prevailing prices. In systems with high shares of solar and wind, variable renewables will be at an increasing disadvantage because their generation will coincide with low or zero price hours.

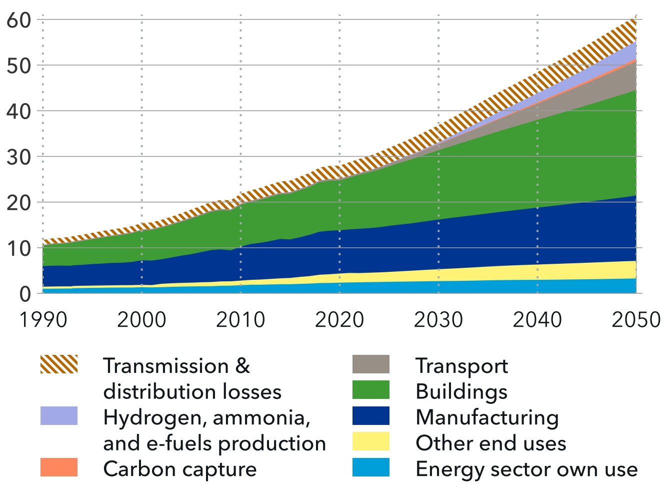
Flexibility and storage
With variable renewable capacity without on-site storage surging by a factor of seven during our forecast period, the global need for flexibility of power systems will almost double. The ability to respond rapidly to sudden changes in load has traditionally heavily favoured conventional power generation, particularly gas and hydropower, as the most cost-effective providers of flexibility. However, as Figure 19 shows, the market for flexibility will diversify and become greatly more competitive, with Li-ion batteries emerging as the primary source of flexibility worldwide, accompanied by other new sources of flexibility and storage such as vehicle-to-grid (V2G) and Power-to-X, while fossil-fired sources dwindle to less than 20% of the flexibility market.

The transition to greater flexibility is not simply a matter of adaptive generation or storage sources, it also requires significant investment in automation and analytics, and innovation in market structures that promote, for example, the adaptive functioning of thermal plants and introduce fresh contract models.

FIGURE 17

World annual electricity demand by segment

Units: PWh/yr

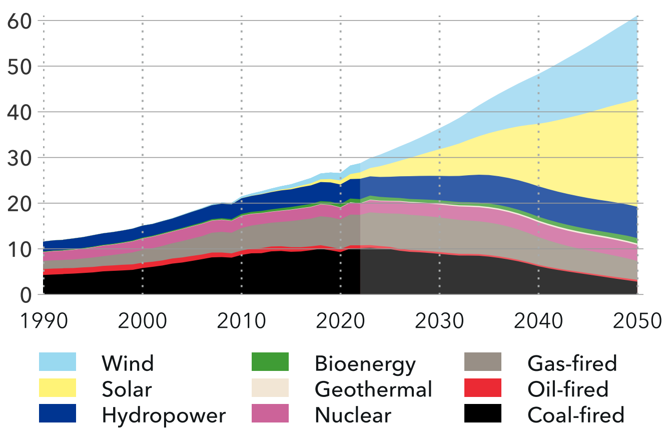


Historical data source: IEA (2023), GlobalData (2023)

FIGURE 18

World grid-connected electricity generation by power station type

Units: PWh/yr

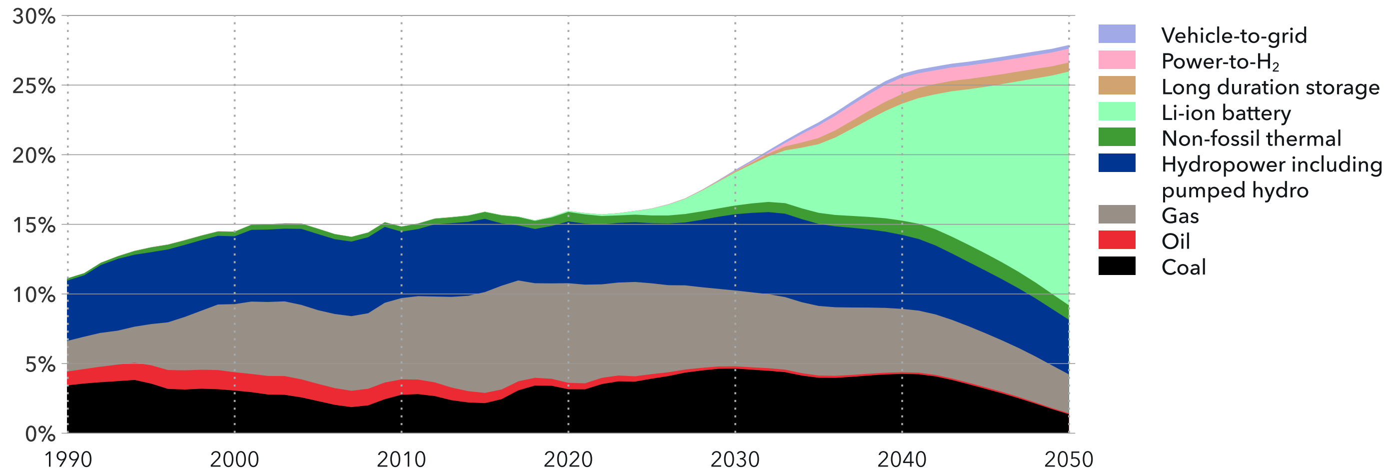


Historical data source: IEA (2023), GlobalData (2023)

FIGURE 19

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

Units: Percentages



We are also seeing the emergence of the rise of smart grid features involving the integration of tools like smart meters, IoT sensors, and advanced automation techniques for more efficient energy flow management and demand side response.

Allied to the need for greater flexibility is the concept of power system adequacy – the ability to consistently meet demand. This becomes most critical at times when the disparity between demand and the sum of solar and wind output – the 'residual load' – is highest. Our analysis shows that this does not necessarily occur at times of high demand, which tend to be well served by variable renewable sources. It is during periods when both solar and wind outputs are at their minimum that the reserve capacity from thermal and hydropower generation becomes essential. However, capacity from these dispatchable sources will be increasingly bolstered (and in fact outcompeted) by solar+storage, V2G, and long-duration storage. Thus not only will thermal generation be crowded out of servicing peak daytime demand by solar and wind, but in many power systems increasingly cheaper storage options coupled with demand side management will come to challenge the very existence of constant, or 'base load', generators like coal or nuclear power.

Grids
Global grid, transmission, and distribution combined will double in length from 100 million c-km in 2022 to 205 million c-km in 2050 to facilitate the fast and efficient transfer of electricity. The same grid will grow 2.5 times in carrying capacity globally. The distribution grid more than doubles to reach about 500 TW-km in mid-century due to the rapid electrification expected in almost all regions, rising peak power demand, and the need for greater capacity to handle higher voltage fluctuations.

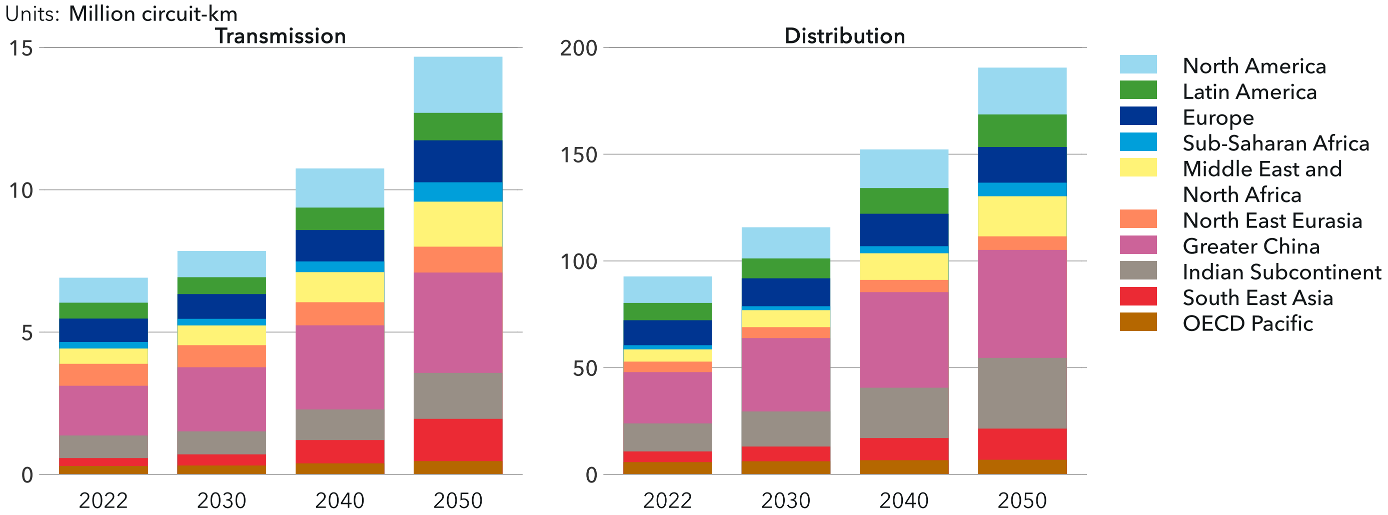
Gridlock

The timing of the grid expansion is critical to the pace of the transition. At present, long planning and permitting timeframes are creating a severe bottleneck for new capacity additions, a situation exacerbated by supply-chain constraints for cables and other grid componentry. Almost 1,000 GW of solar projects are stuck in the inter-connection queue across the US and Europe, close to four times the amount of new solar capacity installed globally last year. While policymakers are starting to address these issues, we factor into our forecast a lower rate of wind and solar capacity addition over the next decade than would be the case in a hypothetical scenario without 'gridlock'.

FIGURE 20

Transmission and distribution power-line length by region

Units: Million circuit-km



HYDROGEN

Indirect electrification through hydrogen and its derivatives is critical for the decarbonization of the hard-to-electrify subsectors of aviation, maritime, heavy transport, and high heat in manufacturing. However, primarily for reasons of cost, it is not on track to scale fast enough to meet Paris Agreement targets.

In our forthcoming *Pathway to Net Zero*, we estimate that hydrogen would need to cover some 15% of world energy demand by mid-century. Our projections indicate hydrogen will make up only 0.25% of the global final energy mix in 2030 and 3% in 2050, although the share of hydrogen in the energy mix of some world regions will be double these percentages.

Although hydrogen's contribution to global energy demand is projected to reach only 3%, the developments in hydrogen technology and infrastructure over the next three decades will be significant. Essentially, this is an entirely new energy source for a growing proportion of the world's energy system and has the potential to transform several industries:

- We forecast that the adoption of e-fuels (mainly e-methanol) in shipping will reach 480 petajoules (PJ) or 3% of the shipping fuel mix in 2030, increasing to 1800 PJ (12%) in 2040 and 2600 PJ (19%) in 2050.
- Together, pure hydrogen and hydrogen-based e-fuels are projected to constitute roughly 16% of aviation energy usage by 2050.
- In manufacturing, hydrogen use will experience gradual growth, reaching nearly 9 EJ/yr. By 2050 – about 6% of the total energy demand in manufacturing by then and 31% of the global demand for hydrogen as an energy carrier. The iron and steel industry will represent the largest portion of hydrogen demand in manufacturing, amounting to 3 EJ/yr or 37% of the total.
- We project a more limited uptake of hydrogen in buildings, reaching approximately 2 EJ/yr in 2050 or just 1.3% of the total energy demand in the buildings sector

The estimated global expenditure on hydrogen production for energy purposes from now until 2050 is expected to reach USD 6.8 trillion, with an additional USD 180bn allocated for hydrogen pipelines and USD 530bn for the construction and operation of ammonia terminals.

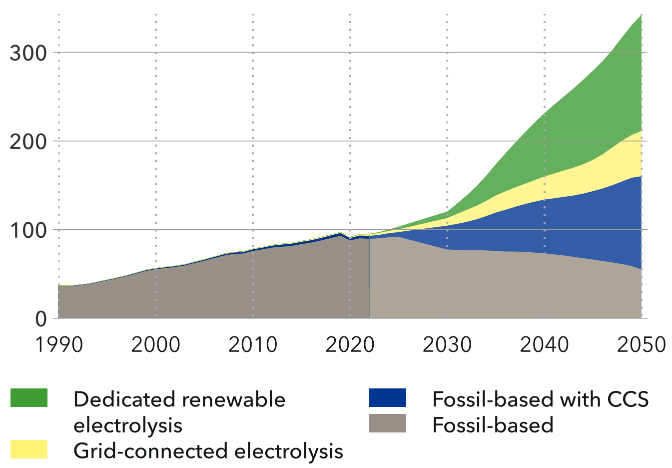
By 2050, an overwhelming 85% of the world's hydrogen supply will originate from low-carbon pathways. This breakdown is as follows: 28% will come from methane reforming with CCS, 15% from grid-connected electrolysis, 28% from dedicated solar-based electrolysis, 7% from dedicated wind-based electrolysis, and 2% from dedicated nuclear-based electrolysis.

Hydrogen will primarily be transported via pipelines for medium distances within and between countries, but it's unlikely to be transported between continents by pipeline. Ammonia, being safer and more convenient for transport – especially by ship – is expected to account for 59% of energy-related ammonia trade between regions by 2050. We anticipate a 20-fold increase in ammonia seaborne transport from 2030 to 2050, totaling 150 million tonnes of shipments at that time.

FIGURE 21

World hydrogen production by production route

Units: MtH_2/yr



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

ENERGY EXPENDITURES

The energy transition involves investments approaching USD 80trn over the next three decades. Some consider this 'unaffordable', yet our results suggest the opposite. Energy expenditure as percentage of global GDP declines from 3.2% in 2022 to 2.0% by mid-century (Figure 22). There is thus a substantial financial upside to the energy transition, paying dividends to society for generations to come, even before factoring in the avoidance of incalculable costs associated with climate change and air pollution.

Total world energy expenditure was USD 5.2trn in 2022. We project world energy expenditure to increase 22% to USD 6.4trn by 2050 – far below the almost doubling of global GDP over the same period. The unit cost of energy will stay stable around USD 12 to 13/GJ, even with a fundamental reshuffling in energy expenditure by source. Between 2022 and 2050, fossil fuel expenditure will reduce 36% in USD terms, non-fossil expenditure will almost triple, and grids expenditure will more than double.

Considering the impact of current inflation and increased policy rates, we have increased the short-term (to 2025) cost of capital by 1.5% for mature technologies and by 1% for emerging technologies compared with last year's assumptions. Although there are regional variations, the future trend in cost of capital is generally increasing most steeply for coal, less steeply for oil and gas, stabilizing over time for variable renewables and nuclear, and declining for low-carbon and renewable hydrogen production.

Household energy expenditure

During the recent energy crisis, energy companies made high profits while household energy bills skyrocketed. Many households have been able to invest in end-use equipment such as EVs and heat pumps that make economic sense over the long term.

We forecast that household energy expenditures (including equipment costs and running costs) in Europe and North America will remain high until energy supply shocks are alleviated and household bills return to 2021 levels in real terms by 2025. Subsequent decades will see a rapid decline of household energy expenditure in North America, to almost half of 2021 levels by 2050, as a result of electrified energy delivered via cheaper renewables (frontloaded by *Inflation Reduction Act* subsidies). In Europe, household energy costs will also decline but not as steeply, reaching 75% of 2021 levels by 2050.

In some other regions, energy bills will go up. In the Indian Subcontinent, for example, the overall trend is towards slowly increasing energy bills, reaching 20% above 2021 levels by 2040. This is due to increasing demand for energy services (such as air conditioning). However, since income per capita will grow by a factor of three, energy costs represent a progressively smaller share of household income across the region.

FIGURE 22

World energy expenditures

Units: Trillion USD/yr

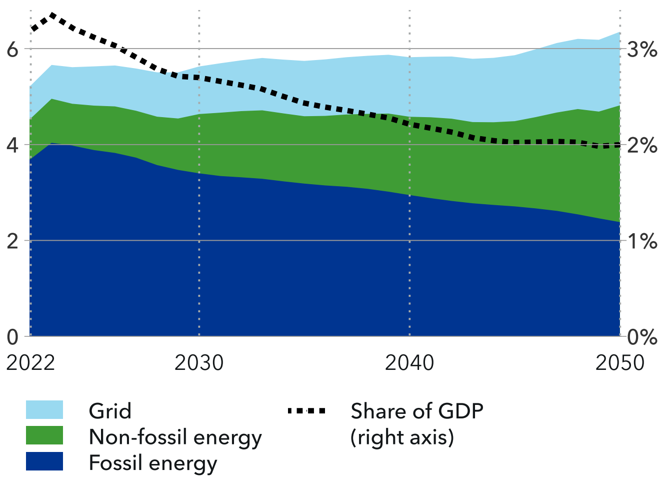
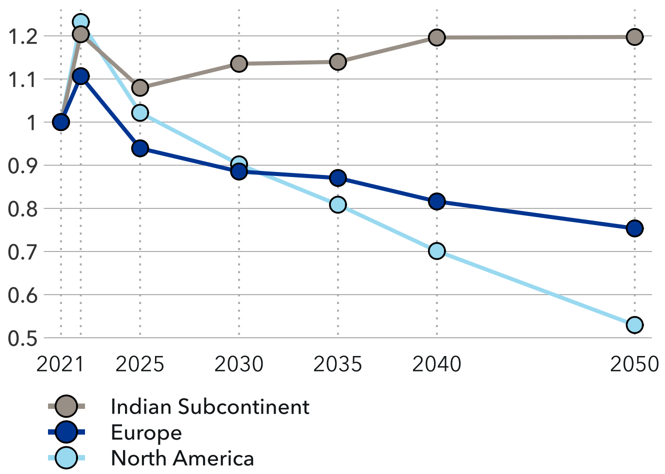


FIGURE 23

Household energy expenditures in selected regions

Units: Unitless, 2021 value = 1



PROGRESSIVE POLICIES

Since last year's Outlook, many countries are progressively intervening in energy systems and aligning climate, industrial, and energy security goals. The priority list for policy makers is long: infrastructure, production capacity, permitting, demand creation, and maintaining energy security while keeping costs under control.

In front-runner regions, the energy transition is propelling a race in industrial policies and support for positioning in clean energy value chains:

- China's comprehensive planning and support direct energy sectors towards 2030 peaking of emissions and 2060 carbon neutrality.
- In the OECD Pacific, Japan's *Green Transformation Policy* (GX) aims to drive economic growth through emissions mitigation.
- In Europe, the EU's *Green Deal Industrial Plan* targets scale in European net-zero capacities and complements the *Fit for 55* package and the *REPowerEU* plan which seeks to reduce dependence on Russian fossil fuels.
- In North America, both Canada and the US have passed key pieces of legislation for decarbonization and clean investment, notably, the US *Infrastructure Investment and Jobs Act* (IIJA) and the *Inflation Reduction Act* (IRA), to speed the development and deployment – at scale – of high cost yet potentially high-return technologies.

The alignment of climate, industry, and energy objectives creates a positive transition dynamic in terms of clean energy acceleration and the 'race to the top' in cleantech. However, while understandable that transition spending aims to accrue primarily domestic benefits, the downside of protectionist policies is slowdown in global cooperation, lack of technology transfer, and technical standards developed separately which risk jeopardizing an effective, harmonized, and global response to address climate change. Furthermore, there is a great risk of medium- and low-income countries being left behind in the cleantech race. Unless sights are set on collaboration and spending on transition opportunities in a globally inclusive manner, emission reductions will fail in the low-income regions, with cascading risks and planetary crisis as the future outcome.

Policy factors in our Outlook

Policy influences all aspects of the energy system, and Figure 24 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

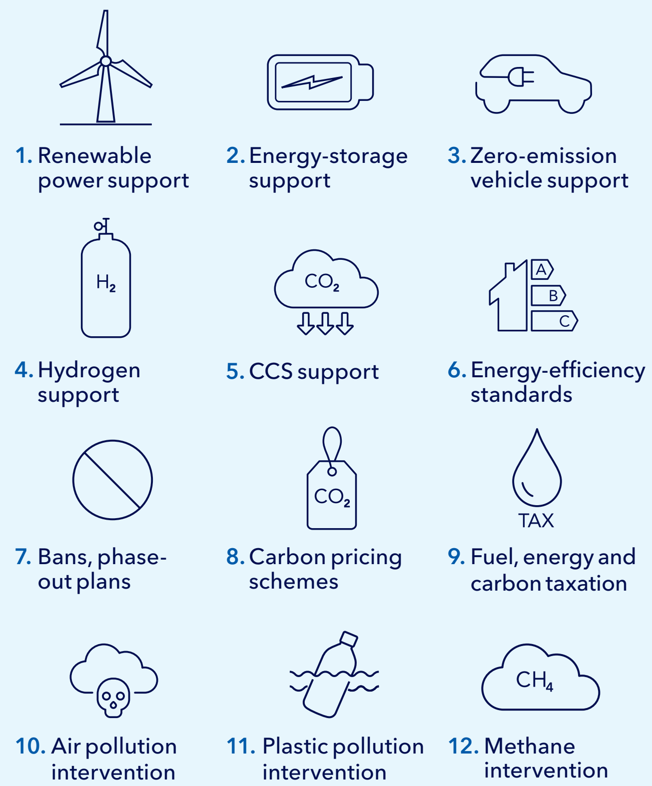
b) Applying technology requirements or standards to restrict the use of inefficient or polluting products/ technologies

c) Providing economic signals (e.g. a price incentive) to reduce carbon-intensive behaviour

We translate country-level data into expected policy impacts, then weigh and aggregate to produce regional figures for inclusion in our analysis.

FIGURE 24

Policy factors included in our Outlook



EMISSIONS

The IPCC (2023) has stated that limiting warming to around 1.5°C requires global GHGs to peak before 2025 at the latest and be reduced by 43% by 2030; at the same time, methane would also need to be reduced by about a third.

While we estimate that energy-related emissions will peak before 2025, they will not halve until after 2050. We expect a small decline in emissions by 2030 (32.1 $GtCO_2$), only slightly lower than 2019 (i.e. pre-COVID-19), and for energy related emissions to be 18.1 $GtCO_2$ by mid-century. Overall emissions in our forecast are associated with global warming of 2.2°C by 2100.[1]

The power sector is currently the largest contributor (40%) to energy-related CO_2 emissions at 13.4 Gt in 2022. The transport sector contributes 25% (8.5 $GtCO_2$) of the total, with manufacturing at 19% (6.3 $GtCO_2$). The rest is made up of buildings emissions and the energy sector's own use.

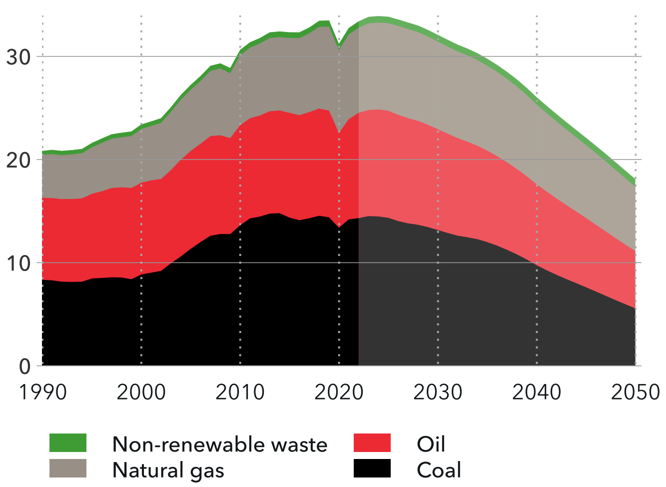
In 2050, the power sector will remain the biggest emitter (30%), but with annual emissions reduced to 5.4 $GtCO_2$. Transport's share will increase to 26% by then, but in absolute terms, its emissions will reduce to 4.8 $GtCO_2$. Emissions from manufacturing decline to 4.2 $GtCO_2$ (23%).

Greater China, currently the largest emitter, will reach peak emissions before 2030 and emissions will fall by 63% from 2022 levels by 2050. The Indian Subcontinent has rapid emissions growth which plateau by the mid-2030s, and 2050 emissions 32% higher than in 2022. Sub-Saharan Africa will show an increase of 33% compared with 2022. All other regions will reduce their energy-related emissions, led by Europe (-83%), OECD Pacific (-80%), and North America (-75%).

FIGURE 25

World energy-related CO_2 emissions by fuel source

Units: $GtCO_2$/yr



Energy-related CO_2 emission capture

Total commercial CCS capacity in 2022 was 43 $MtCO_2$ per year, with a five-fold expansion in that capacity either in construction or in various stages of development. We expect power and manufacturing sectors will increase the capture of carbon from their processes and waste streams. Additionally, we expect all carbon emissions from hydrogen production as an energy carrier to be captured.

In the near term, by 2025, the largest contributor to CCS will be the natural gas processing industry with a share of about 40%. By the year 2050, the total energy-related captured CO_2 is estimated to reach 1.25 $GtCO_2$, with ammonia accounting for 46%, followed by e-fuel at 14%, and hydrogen at 8%.

In 2050, North America will have the highest capacity of CCS (19%) followed by Europe and North East Eurasia, both around 17%. Globally, CCS in 2050 captures just 6% of energy-related CO_2 emissions.

Direct Air Capture (DAC)

DAC, which refers to the process of removing CO_2 from the atmosphere, is still an emerging technology that is energy- and equipment-intensive. However, in the longer term, we expect that DAC will contribute to removing just above 200 $MtCO_2$/yr by 2050, mostly in Europe, North America and OECD Pacific.

1. As we explain in detail in our main report, to calculate the global warming implications of our forecast we take into account both energy-related CO_2 emissions (about 70% of total GHGs) and processes that produce CO_2 through a chemical reaction (e.g. cement and other industrial processes). We also factor in methane emissions from energy related and other industrial processes as well as both CO_2 and methane released by agriculture, forestry, and other land-use.

CLOSING THE GAP TO 1.5°C

Ahead of COP 28 this year, we will be releasing an update to our *Pathway to Net Zero* report 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 emissions gap?

In 2022, energy-related CO_2 emissions experienced a 2% increase compared to 2021, reaching a total of 33.4 $GtCO_2$. We expect a further 2% increase over the next two years before gradually declining to 18.1 $GtCO_2$ by mid-century, 46% less than in 2022. In our *Pathway to Net Zero*, the emissions reduction efforts are notably more aggressive, with an average annual reduction of 1.2 $GtCO_2$ leading to 2.2 Gt of energy-related emissions by the year 2050. These emissions are either captured and sequestered or compensated for by net negative emissions technologies.

Between 2050 and 2100, we assume that net annual energy-related emissions reduce slowly from 23 $GtCO_2$ towards zero at or near the turn of the century. By contrast, our *Pathway to Net Zero* has net-negative annual emissions from 2050.

Figure 26 below shows carbon budgets in relation to our emissions forecast. Carbon budgets refer to the amount of GHGs that can be emitted for a given level of global warming above pre-industrial levels. In our most likely energy future the 1.5°C carbon budget is exhausted in 2029 and the 2.0°C carbon budget is exhausted in 2054.

How to close the 0.7°C gap?

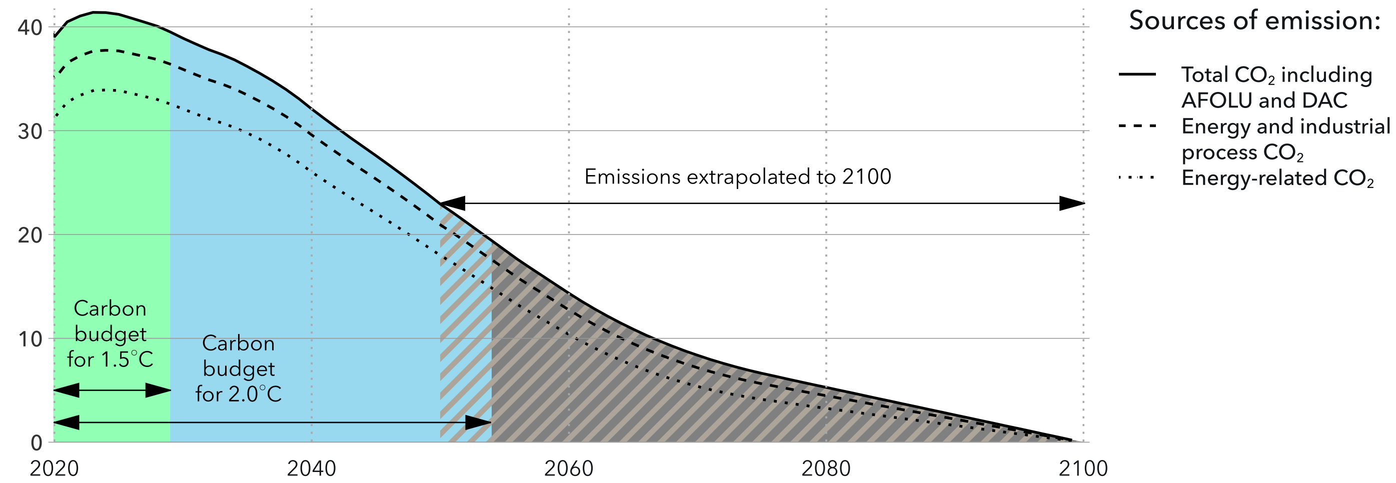
The gap must be closed by a combination of:

- Reduced combustion of fossil fuels and replacing coal, oil, and gas with electricity from 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)

FIGURE 26

World CO_2 emissions and associated carbon budgets

Units: $GtCO_2$/yr

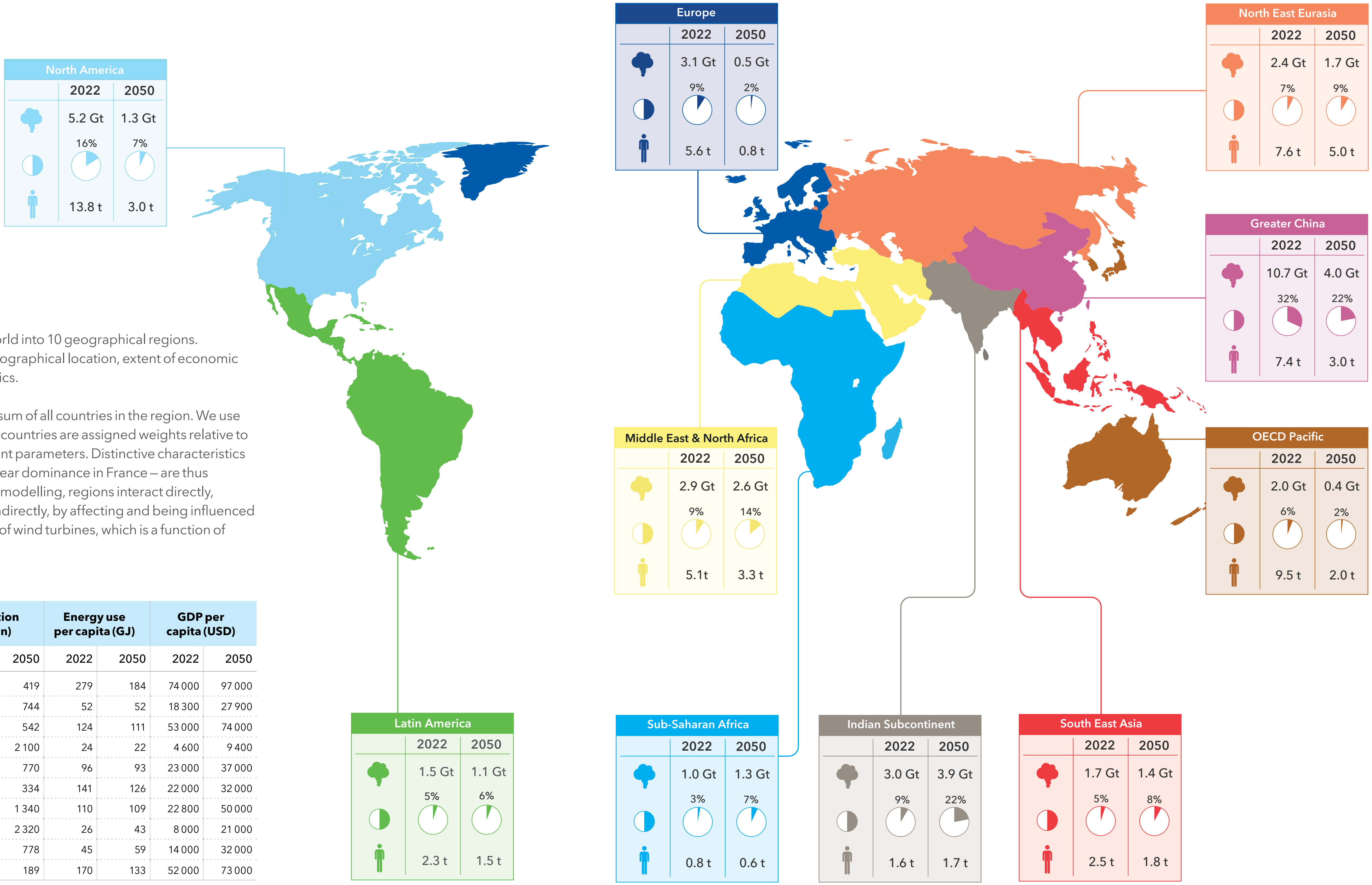


Energy-related regional emissions

Total energy-related CO_2 emissions

Share of world emissions

Energy-related per capita emissions



10 world regions

In this Outlook, we have divided the world into 10 geographical regions. These regions are chosen based on geographical location, extent of economic development, and energy characteristics.

Each region's input and results are the sum of all countries in the region. We use relevant, weighted averages, such that countries are assigned weights relative to population, energy use, or other relevant parameters. Distinctive characteristics of certain countries – for example, nuclear dominance in France – are thus averaged over the entire region. In our modelling, regions interact directly, through trade in energy carriers, and indirectly, by affecting and being influenced by global parameters, such as the cost of wind turbines, which is a function of global capacity additions.

	Population (million)		Energy use per capita (GJ)		GDP per capita (USD)	
Region	2022	2050	2022	2050	2022	2050
North America (NAM)	373	419	279	184	74 000	97 000
Latin America (LAM)	688	744	52	52	18 300	27 900
Europe (EUR)	543	542	124	111	53 000	74 000
Sub-Saharan Africa (SSA)	1 200	2 100	24	22	4 600	9 400
Middle East & North Africa (MEA)	536	770	96	93	23 000	37 000
North East Eurasia (NEE)	320	334	141	126	22 000	32 000
Greater China (CHN)	1 450	1 340	110	109	22 800	50 000
Indian Subcontinent (IND)	1 880	2 320	26	43	8 000	21 000
South East Asia (SEA)	688	778	45	59	14 000	32 000
OECD Pacific (OPA)	207	189	170	133	52 000	73 000

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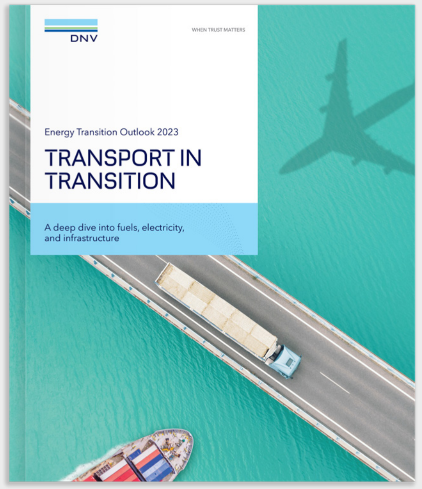

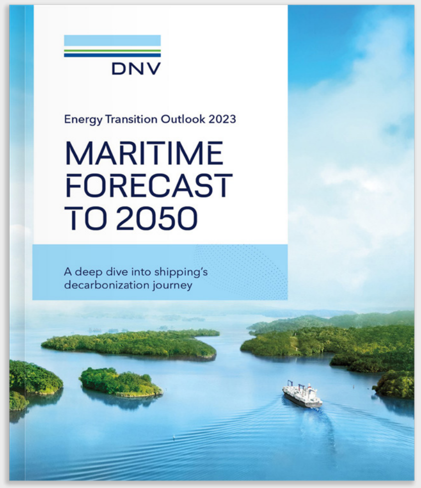

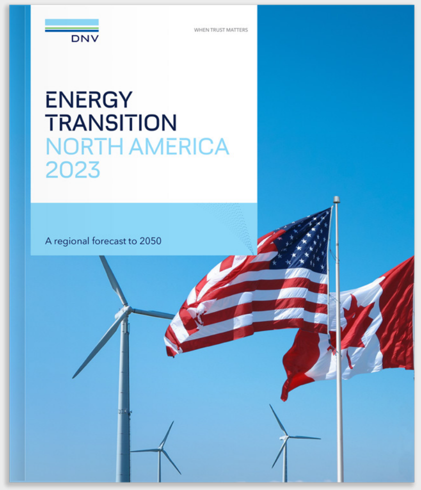

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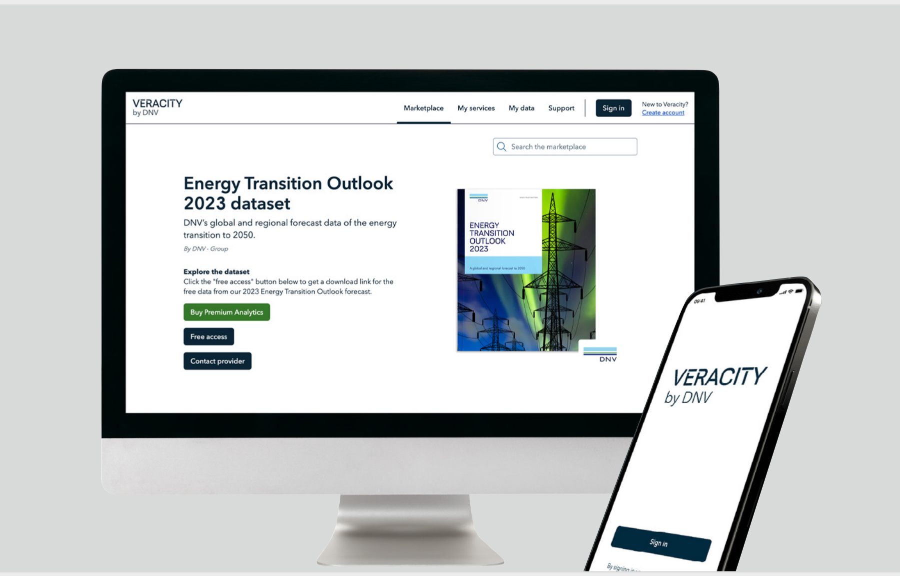
Don't miss the launch of our *Pathway to Net Zero* report ahead of COP28 in November 2023



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.

dnv.com/eto-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 Research & Development division, based in Oslo, Norway. In addition, we have been assisted by internal and external energy transition experts, with the core names listed below:

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

Published by DNV AS. **Design** SDG/Minnesota Agency. **Print** Aksell. **Paper** 150 gram silk.
Images Cover image: Getty Images

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