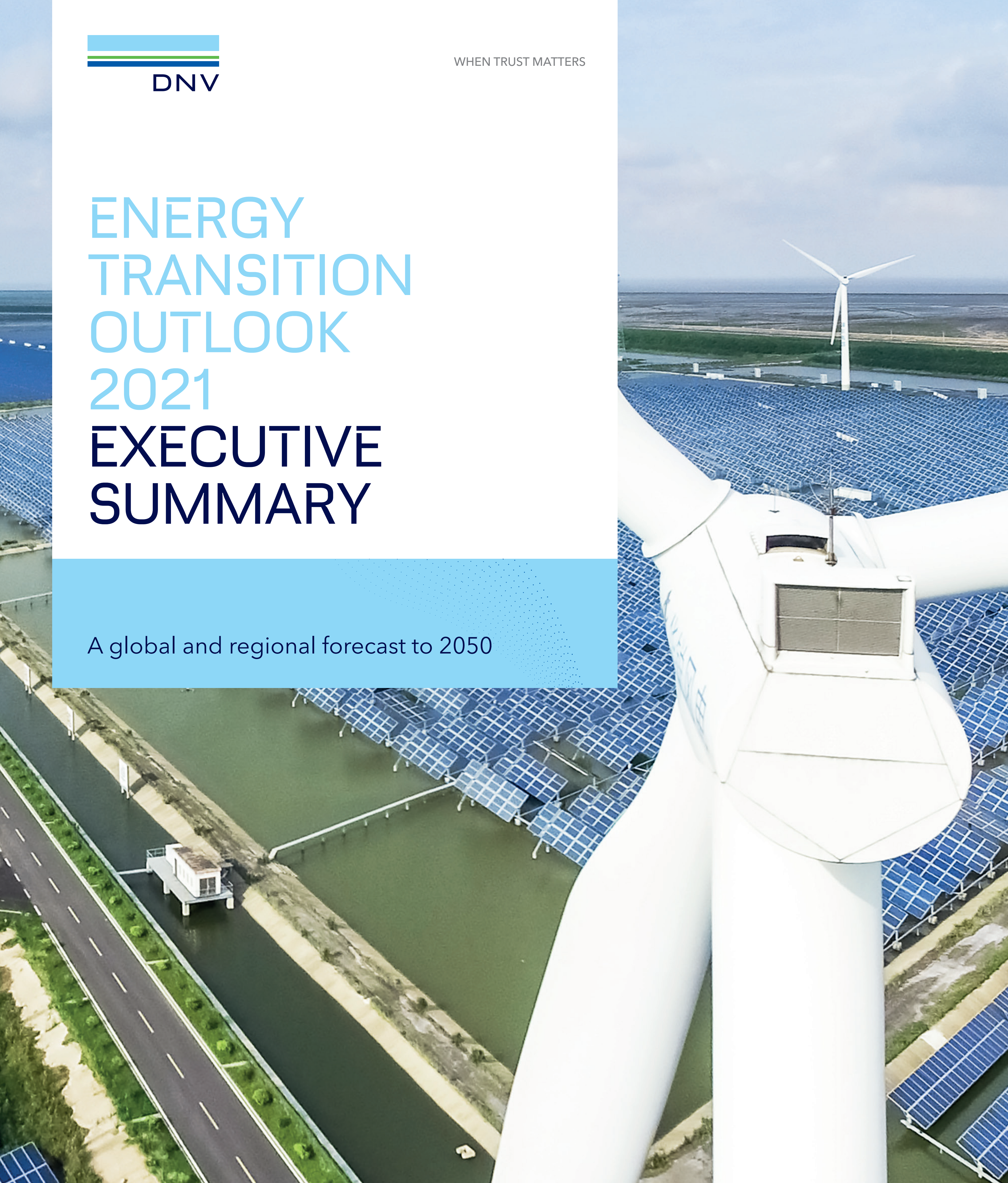
WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK 2021 EXECUTIVE SUMMARY

A global and regional forecast to 2050



FOREWORD

This is the fifth annual Energy Transition Outlook issued by DNV. For half a decade, we have said, consistently, that the most likely future for the world's energy system is one that will result in global warming exceeding 2°C by 2100, and that is our conclusion once again this year.

The impact of global warming is becoming alarmingly apparent, and I believe there is a widening understanding of the long-term risks for humanity. However, while perceptions may have changed, reality has not. Each year, in the foreword to this Outlook, I have stressed the need for governments and companies to take decisive action on climate change. COVID-19 has more than demonstrated that governments can act boldly. Yet, from an energy transition perspective, the pandemic has been a lost opportunity. Recovery packages have largely focused on protecting rather than transforming existing industries. There are exceptions to this, and our forecast incorporates slightly more clean energy in the mix over the next three decades than we did a year ago.

But large-scale action is still needed urgently, and our forecast provides clear guidelines on where such efforts should be directed. Wind and solar PV will expand 15- and 20-fold respectively in our forecast period. Twinned with the plunging costs and advancing technology of battery storage, variable renewables are already enabling a phase out of thermal power generation and the business case will become overwhelming by 2030.

Electricity demand will more than double by 2050 and by then over 80% of power will be provided by non-fossil sources. The accompanying efficiencies are staggering, both in the avoidance of heat losses in power generation and in end use – for example, with EVs and heat pumps. But the problem is this: even if all electricity was 'green' from this day forward, humanity would still fail to achieve net zero emissions by 2050.

Not everything can be electrified. That is what makes tackling the hard-to-abate sectors of high heat, aviation, shipping and trucking so very urgent. Yet our forecast shows that hydrogen enters the picture at scale only in the late 2030s. That is far too late: climate science points to the considerable risks of allowing emissions to accumulate before we act.

The verdict is clear: the world needs vastly more green electricity, both direct and indirect, more biofuel, and more carbon capture and storage on a dramatically accelerated timescale.

In October this year we will publish our first *Pathway to net zero emissions* report – a detailed look at how best to close the gap between this forecast and one that is aligned with the Paris Agreement. It is vital that we mobilize all the forces of the Fourth Industrial Revolution towards a green energy transformation, including innovative ways to finance this shift. This year we address that critical subject in our supplementary report – *Financing the Energy Transition*.

Remi Eriksen

Group president and CEO

DNV

Highlights

CORE INSIGHTS

1. **We are not meeting Paris ambitions; there is a very short window to close the gap**
   - Global energy-related emissions will fall only 9% by 2030, and the 1.5˚C carbon budget is emptied by then
   - We estimate the global average temperature increase to reach 2.3˚C by end of the century

2. **Electrification is surging ahead, and renewables will outcompete all other energy sources**
   - Electrification of final energy demand will grow from 19% to a 38% share by 2050, powered mainly by solar and wind
   - 50% of all passenger-vehicle sales will be EVs in 2032
   - Heat pump use will triple, providing 32% of heat in 2050 while consuming 9% of energy use for heating

3. **Efficiency gains lead to a flattening of energy demand from the 2030s**
   - Energy efficiency remains our greatest untapped resource against climate change
   - Energy intensity (unit of energy per dollar of GDP) improvements at 2.4%/yr outpace GDP growth during the coming three decades
   - Efficiency gains are driven mainly by electrification

4. **Fossil fuels are gradually losing position, but retain a 50% share in 2050**
   - Gas maintains its current position, oil demand halves, and coal falls to a third of current use by 2050
   - CCS deployment is too slow, and only 3.6% of fossil CO_2 emissions are abated in 2050

NEW INSIGHTS 2021

1. **COVID-19 economic recovery spending is a lost opportunity**
   - Apart from the EU, COVID-19 stimulus packages are largely locking in carbon-intensive systems

2. **Variability and low power prices are not roadblocks to a renewable-based power system**
   - Power-to-X, storage, connectivity, demand response, and carbon pricing will all help solar PV and wind maintain their competitiveness
   - Solar + storage is emerging as a new power plant category which will provide 12% of all grid-connected electricity by 2050

3. **Decarbonizing hard-to-abate sectors requires far greater scaling of hydrogen, e-fuels, and biofuels**
   - Combined, hydrogen and e-fuels will cover only 5% of global energy demand by 2050
   - Aviation, maritime, and heavy industry increase their relative share of emissions and remain heavy users of unabated fossil fuels

4. **Most hydrogen will be produced from dedicated renewables-based electrolysers by 2050**
   - Green hydrogen will dominate over time, with 18% of hydrogen supply produced via electrolysis from cheap grid electricity and 43% from electrolysis using dedicated off-grid renewables
   - Blue hydrogen will lose its cost advantage, providing only 19% of hydrogen supply for energy purposes by 2050

Highlights – Core insights

We are not meeting Paris ambitions; there is a short window of opportunity to close the gap

Global emissions likely peaked in 2019, followed by an unprecedented 6% drop in 2020 due to COVID-19. Emissions are now rising sharply again and will grow for the next three years before starting to decline.

While they are being added at great speed, renewables currently often supplement rather than fully replace thermal power generation. By 2030, global energy-related CO_2 emissions are likely to be only 9% lower than 2019 emissions, and by 2050 only 45% lower. This is in sharp contrast to ambitions to halve GHG emissions by 2030 and to achieve the net zero emissions by 2050 required to limit global warming to 1.5˚C. Our forecast is that we are most likely headed towards global warming of 2.3˚C by 2100.

As CO_2 emissions continue to accumulate, the window of opportunity to act narrows every year. Relying on large-scale net-negative emissions technologies and carbon removal in the latter half of the century is a dangerous, high-risk approach. With global warming, every fraction of a degree is important, and all options to reduce emissions need urgent realization.

Electrification is surging ahead, and renewables will outcompete all other power sources

Electrification is by far the most dynamic element of the energy transition. The share of electricity in final global energy demand is set to double from 19% to 38% within the next 30 years.

Solar PV and wind are already the cheapest form of new power almost everywhere, and within a decade will also be cheaper than operating existing thermal power in most places. By 2050, solar and wind will represent 69% of grid-connected power generation, and fossil power just 13%. Connectivity, storage and demand-response will be critical assets in the decarbonized power system.

On the demand side, passenger and commercial EV uptake is rising quickly in Europe, China and to some extent the US. Government incentives, cost reductions and technology improvements in both batteries and charging infrastructure will drive a rapid expansion. By 2032, half of all new passenger vehicles sold globally will be electric, with some regions lagging owing to infrastructure challenges. In buildings, heat pumps use will triple, providing 42% of space heat in 2050 while consuming only 15% of energy used for space heating.

FIGURE 1

World energy-related CO_2 emissions

Units: $GtCO_2$/yr

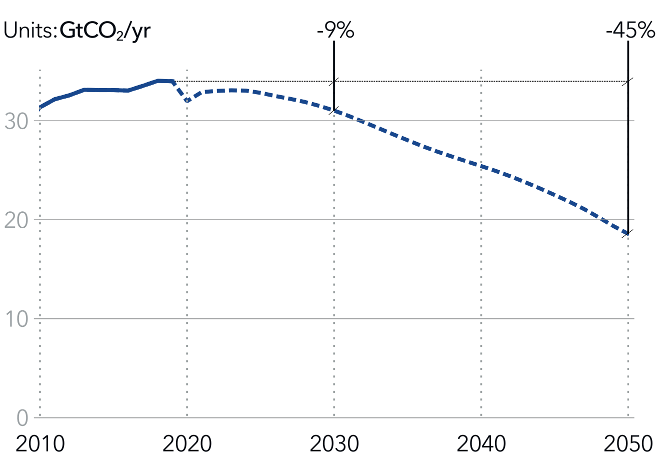
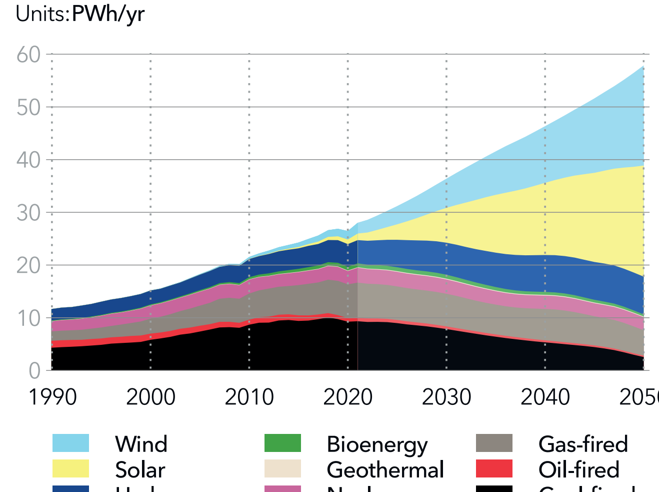


FIGURE 2

World grid-connected electricity generation by power station type

Units: PWh/yr



Historical data source: IEA WEB (2020), GlobalData (2021)

Efficiency gains lead to a flattening of energy demand from the 2030s

Energy efficiency is the unsung hero of the energy transition and should be the number one priority for companies and governments. Many efficiency measures have marginal or even negative costs, but due to split incentives and/or a lack of long-term thinking, industry standards and regulations are needed to ensure implementation.

Energy intensity (unit of energy per dollar of GDP) improvements will average 2.4%/yr during our forecast period – against the 1.7%/yr average over the last 20 years. Most of the accelerated efficiencies are linked to electrification, with the remainder coming largely from efficiency improvements in end uses, such as better insulation. The largest efficiency gains happen in the transport sector, but there are significant gains also in manufacturing and buildings.

Overall efficiency gains will result in a levelling off in global energy demand despite a population increase of 22% and the global economy growing 111% over the next 30 years. Global energy demand will grow only 8% from 2019 to 2035, thereafter remaining essentially flat the next 15 years.

Fossil fuels are gradually losing position, but retain a 50% share in 2050

Fossil fuels have held an 80% share of the global energy mix for decades. We forecast that, by mid-century, fossil fuels will decrease, but still hold a 50% share of the energy mix, a testament to the inertia of fossil energy in an era of decarbonization.

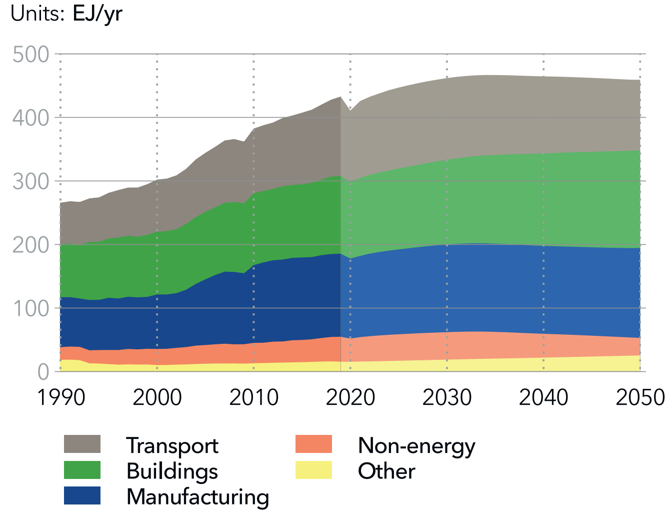
Coal use will fall fastest, down 62% by 2050. Oil use stays relatively flat until 2025 when it starts a steady decline, to just above half of current levels by mid-century. Gas use will grow over the coming decade, then levels off for a 15-year period before starting to reduce in the 2040s. Gas will surpass oil as the largest energy source and will represent 24% of global energy supply in 2050.

Decarbonized fossil energy is an important aspect of reaching the Paris Agreement, but the uptake of carbon capture and storage (CCS) is forecast to be woefully slow, mainly for reasons of cost, with just 3.6% of fossil CO_2 emissions abated in 2050.

FIGURE 3

World final energy demand by sector

Units: EJ/yr

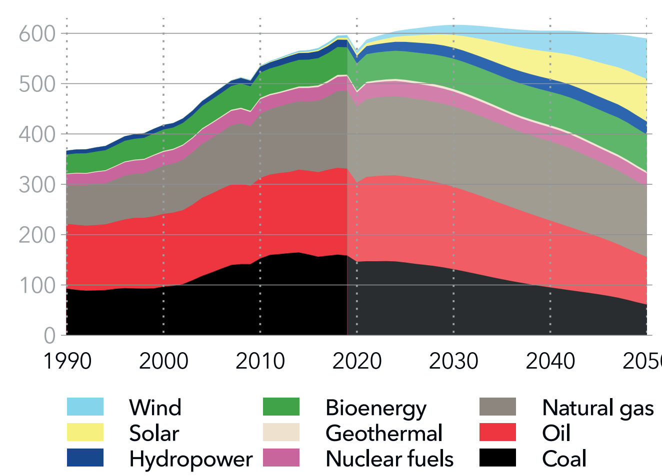


Historical data source: IEA WEB (2020)

FIGURE 4

World primary energy supply by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

Highlights – New insights

COVID-19 economic recovery spending is a lost opportunity

Government interventions, to stop the spread of the virus and then to restart activity, revealed how effective national and global actions can be. Similar action and funding have yet to be applied to the unfolding global climate crisis.

The trillions of dollars pushed into the global economy over the past 20 months have mainly been directed towards emergency measures like wage supplements and on building back the existing economic and industrial engine. Yet the opportunity for a green reset of production, transport and economic activity was unique, and as we wrote in ETO 2020, "The post-COVID-19 stimulus packages hold the potential to alter the speed of the transition." With some notable exceptions, particularly in the EU, governments have not steered recovery spending towards a decarbonized outcome.

Global CO_2 and GHG emissions fell 6% in 2020 but will rise again this year. While the emissions trajectory has shifted down slightly, that is due to lost economic activity, not energy-system renewal. The overall pace of the transition has not accelerated, and that is a lost opportunity.

Variability and low power prices are not roadblocks to a renewable-based power system

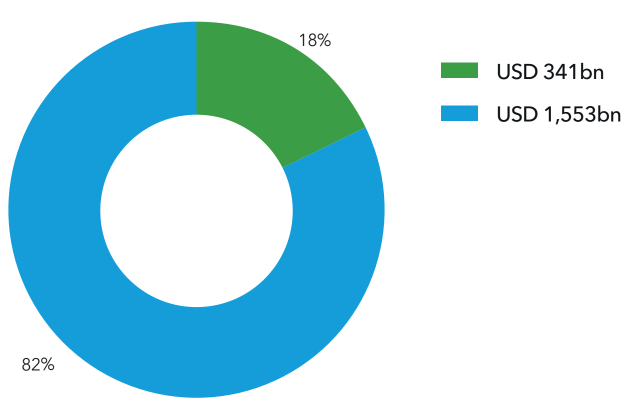
The present power system is not set up for variable renewables as the dominant source of production. Yet plunging costs, government support for renewable power buildout, and carbon pricing will ensure that renewables will eventually dominate power generation. Over the coming 30 years, USD 12 trillion will be invested in both building a larger grid and adapting it to the variability of solar and wind through technical solutions such as connectivity, storage, and demand response.

The cost of power from solar and wind will continue to reduce but price cannibalization threatens the investment case for renewable capacity if cheap power is unused at times of ample supply. However, indirect electrification through power-to-X will require massive renewable electricity production, and along with various storage solutions, will ensure that surplus power will be used, and capture prices maintained at a satisfactory level.

Solar PV + storage will make solar more directly competitive with thermal generation, nuclear and hydropower. We find that one third of all solar production will be built with direct storage, and by 2050, solar PV + storage will produce 12% of all grid-connected electricity.

FIGURE 5

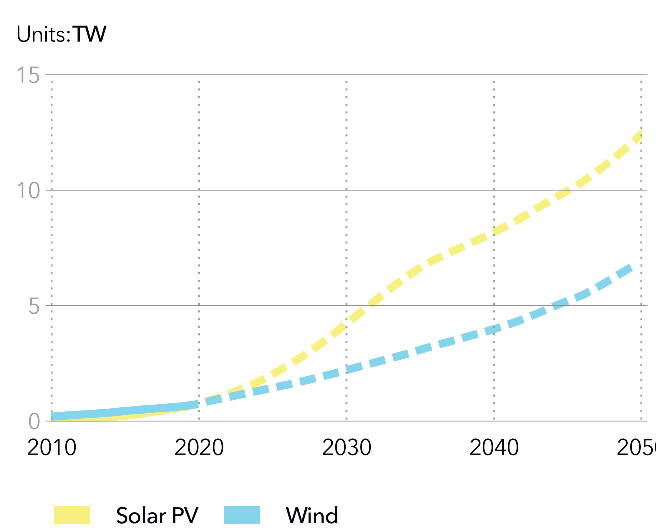
Pandemic recovery spending 2020



Source: UNEP report 'Are we building back better', Feb 2021
Note: In a separate report the IEA's Sustainable Recovery Tracker estimated that as of Q2 2021, clean energy measures totalled USD380bn or just 2% of total fiscal support related to COVID-19

FIGURE 6

Build-up of solar and wind - global installed capacity



Includes off-grid capacity for wind and solar. Historical data: GlobalData (2021)

Decarbonizing hard-to-abate sectors requires far greater scaling of hydrogen, e-fuels, and biofuels

Hard-to-abate sectors are those that cannot easily be decarbonized through electrification, and include aviation, maritime, long-haul trucking and large parts of heavy industry. These sectors are currently responsible for around 35% of global CO_2 emissions, and progress in reducing these emissions is stubbornly slow.

Hydrogen is seen as the main decarbonization alternative for these sectors, with biofuels in a supporting role, mainly in aviation. Direct hydrogen use is often not suitable, and ships and aircraft require hydrogen derivatives and e-fuels such as ammonia and synthetic jet fuel.

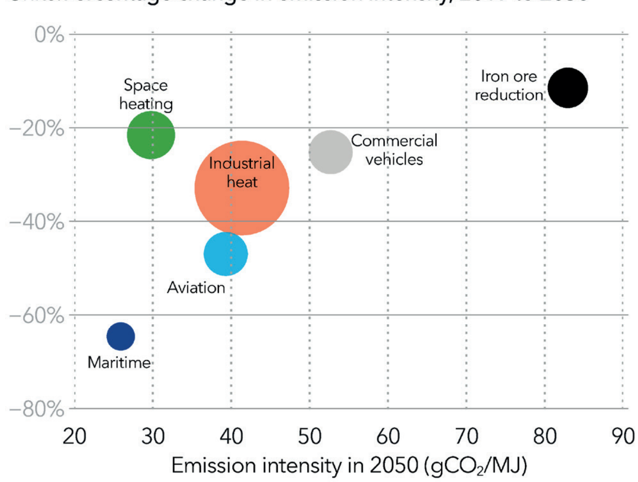
Global hydrogen production for energy purposes is currently negligible and will only start to scale from the late 2030s, meeting 5% of global energy demand by 2050. Government incentives, similar to those given to renewables, are needed to stimulate technology development and accelerate uptake of hydrogen and e-fuels.

Aviation, maritime and heavy industry thus retain high unabated fossil-fuel shares towards 2050, slowing the transition and significantly impeding the achievement of the Paris Agreement.

FIGURE 7

CO_2 emissions of hard-to-abate sectors by 2050

Units: Percentage change in emission intensity, 2019 to 2050



Bubble area is proportional to emissions in 2050.

Most hydrogen will be produced from dedicated renewables-based electrolysers by 2050

The current production of hydrogen as an energy carrier is negligible compared with the 75m tonnes of grey/brown hydrogen produced annually for fertilizer and chemicals production.

Blue hydrogen, produced by steam methane reforming (SMR) from gas with CCS, will replace some of the grey and brown hydrogen in the coming decades. In total, blue hydrogen will also comprise 18% of hydrogen supply for energy purposes by 2050.

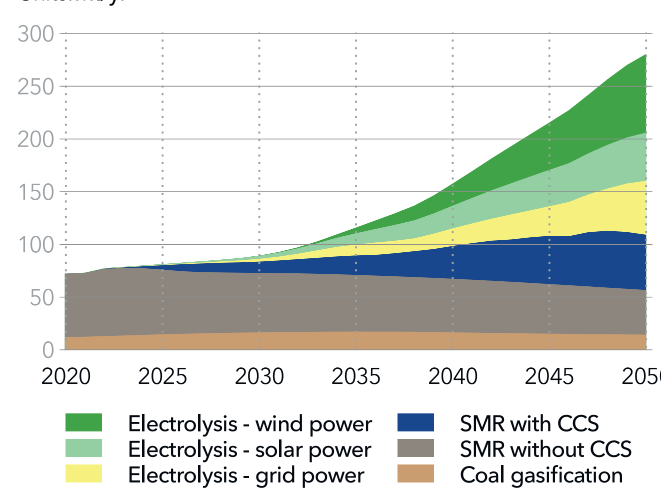
Green hydrogen from electrolysis will be the main long-term solution for decarbonizing hard-to-abate sectors, including hydrogen as a basis for other e-fuels.

Electrolysis powered by grid electricity is disadvantaged by the limited number of hours of low-priced electricity. Its CO_2 footprint will, however, improve as more renewables enter the power mix. The future production of hydrogen for energy purposes will be dominated by electrolysis using dedicated off-grid renewables, such as solar and wind farms. By 2050, 18% of hydrogen will be grid-based and 43% will come from dedicated capacity comprising solar PV (16%), onshore wind (16%) and fixed offshore wind (9%).

FIGURE 8

World hydrogen production by source

Units: Mt/yr



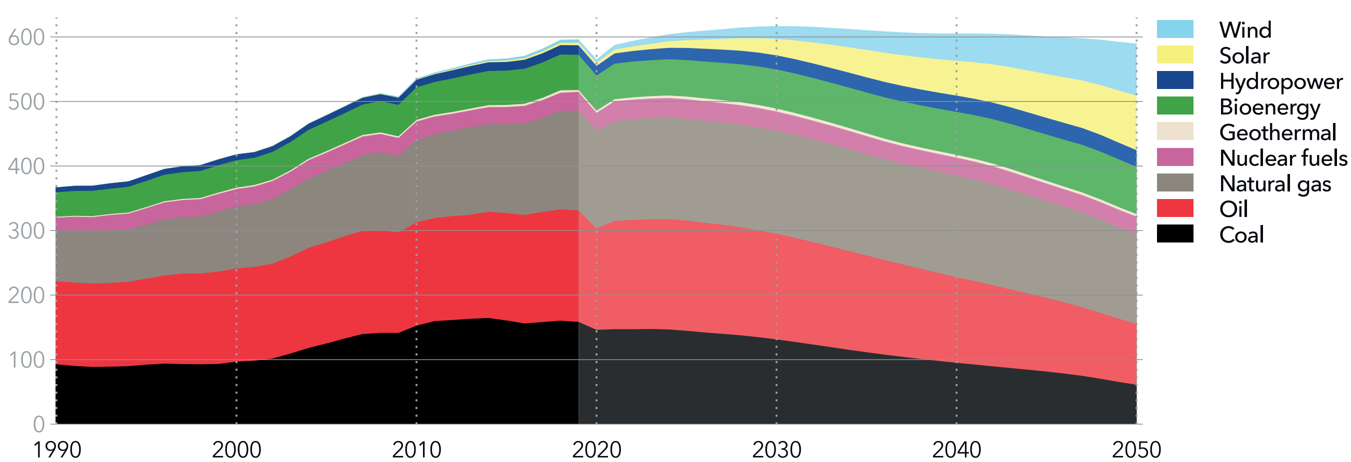
PRIMARY ENERGY 2019-2050

Shown here is our forecast for primary energy through to 2050. Primary-energy supply is the total amount of energy behind the provisioning of energy services. Considerable losses occur in the conversion and transport of energy (currently exceeding 100 EJ annually) and these are included in primary energy numbers, as is the energy industry's own use of energy, which is considerable – typically 7% of primary energy consumption. Primary energy, which was 594 EJ before the pandemic, will return to 2019 levels in 2022, but will then only increase by a further 4% percent and peak at 617 EJ in 2030 before slowly reducing by 4% to some 590 EJ in 2050.

FIGURE 9

World primary energy supply by source

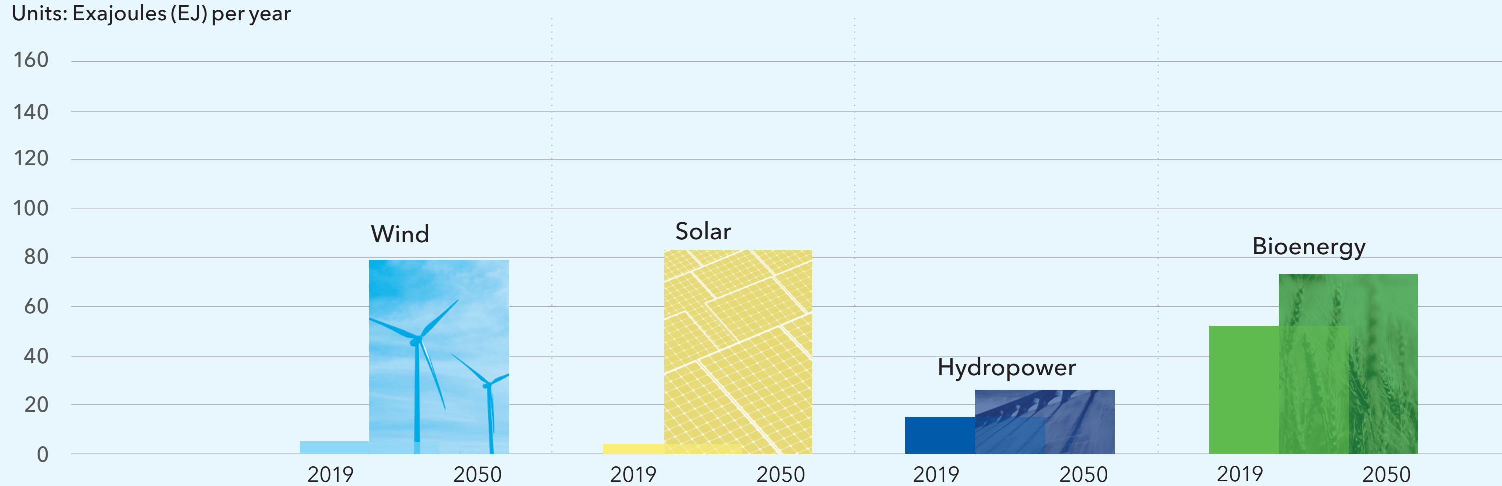
Units: EJ/yr



Historical data source: IEA WEB (2020)

World Energy Supply Transition 2020-2050

Units: Exajoules (EJ) per year

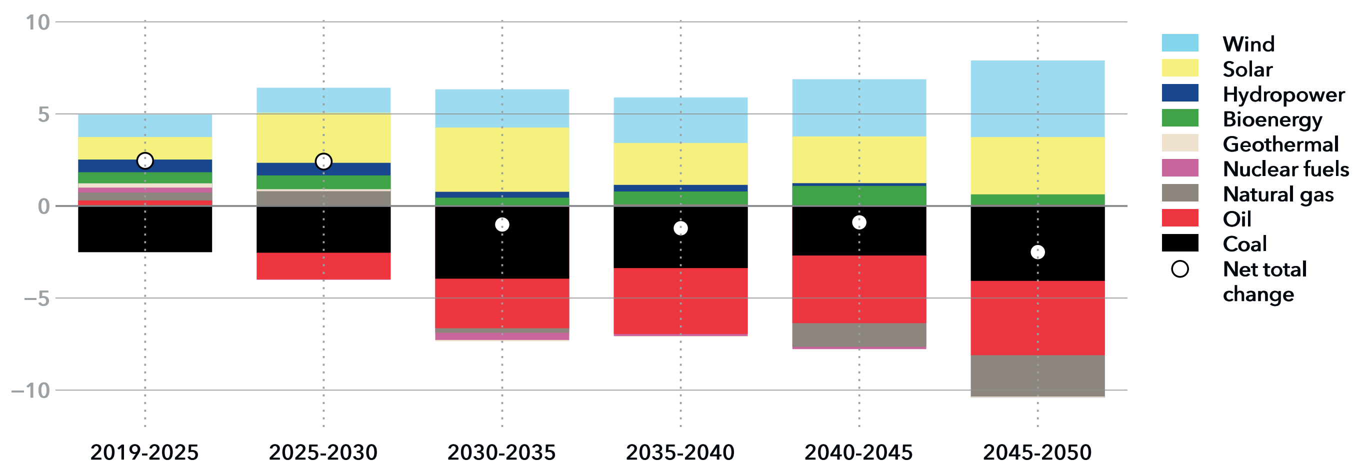


Contributions to changes in the primary-energy supply are shown in the figures below. In the forecast period, renewables will constantly be adding to the primary-energy supply, while fossil fuels will be reducing, except for natural gas, which only decreases in the 2040s. The fossil share of the energy mix will fall from 80% today to 50% by mid-century. Nuclear will be stable at 5% over the entire period, while renewables will triple from 15% today to 45% by the end of this forecast period.

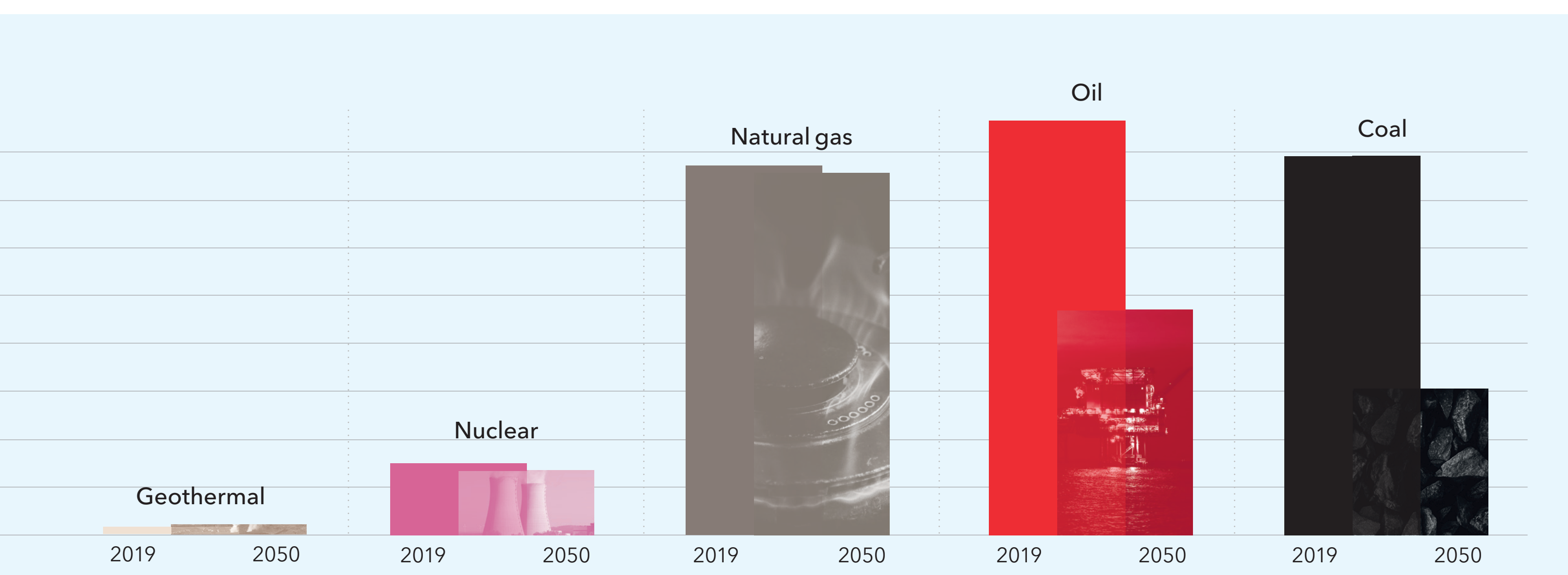
FIGURE 10

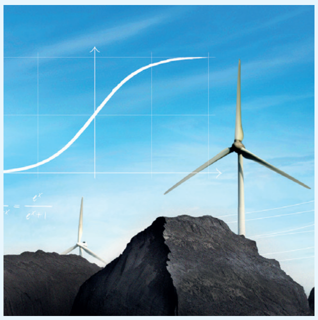
Net change in primary energy supply by source

Units: **EJ/yr**



Net change of primary energy between 5-year intervals. 2019 used to avoid effect of COVID-19. Historical data source: IEA WEB (2020)





ENERGY TRANSITION OUTLOOK 2017

ENERGY TRANSITION OUTLOOK 2018

ENERGY TRANSITION OUTLOOK 2019

ENERGY TRANSITION OUTLOOK 2020

After five years of forecasting…

Our findings this year do not differ fundamentally to those of our first forecast issued four years ago. Over the years, we have extended and refined our model, for example by delving deeper into the dynamics of the key demand sectors of transport, manufacturing and buildings. We have also added additional energy carriers and sectors such as hydrogen, floating offshore wind and solar PV+storage, and introduced the modelling of power generation on an hourly basis. But one of our key findings – that the global energy mix will be split in roughly equal shares between fossil and non-fossil sources by 2050 – has not changed. Neither has our conclusion that the world will fail to achieve the climate goals of the Paris Agreement by an alarming margin.

The fact that these findings have remained consistent is a major cause of concern: In a half-decade where the costs of inaction on climate change have been mounting and the evidence of its effects are growing ever more visible, it is sobering to reflect on the fact that the pace of the energy transition has not accelerated beyond our first forecast.

About this Outlook

This annual Outlook presents the results from our independent model of the world's energy system. It covers the period through to 2050 and forecasts the energy transition globally and in 10 world regions. Our forecast data may be accessed at eto.dnv.com/data. More details on our methodology and model can be found on page 34. The changes we forecast hold significant risks and opportunities across many industries. Some of these are detailed in our supplements:

- Maritime forecast
- Financing the energy transition
- Technology progress report
- Pathway to net zero emissions

Independent view

DNV was founded 157 years ago to safeguard life, property and the environment. We are owned by a foundation and are trusted by a wide range of customers to advance the safety and sustainability of their businesses. 70% of our business is related to the production, generation, transmission and transport of energy. Developing an independent understanding of, and forecasting, the energy transition is of strategic importance to both us and our customers.

The impact of COVID-19

The impact of the pandemic is beginning to recede in developed countries where half the adult population will be fully vaccinated by the end of Q3. Vaccination in the developing world lags far behind; some countries have barely begun their rollouts. GDP impact differs strongly across world regions, but overall, we follow the IMF's expectation (April 2021) of a rebound of 6.1% in 2021 and 4.9% in 2022. COVID-19 results in a 2023 global economy that has lost 4.1% of GDP compared with pre-pandemic projections. This loss is almost permanent, but 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 declines to 3.2%.

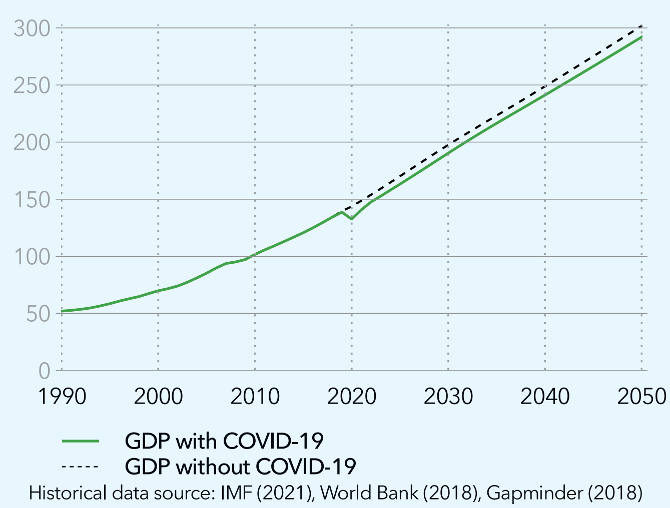
From an energy perspective, the pandemic will leave certain lasting effects in its wake. Working from home will intensify, reducing the demand for workspace by 5% compared with our pre-pandemic estimates in developed regions (including China), and by half of that in developing and emerging economy regions. The energy intensity of workplaces will reduce but that will be counterbalanced by a rise in residential energy demand. In developed regions the increase is 4%, half of which arises from bigger dwelling sizes and half from increased requirements for heating and cooling.

We expect a permanent drop in work-related air travel of 20% compared with our pre-pandemic forecast. Leisure travel, which account for two thirds of air miles, is likely to rebound fully by 2024.

FIGURE 11

World GDP - with and without COVID-19

Units: Trillion USD/yr



Historical data source: IMF (2021), World Bank (2018), Gapminder (2018)

> Very little of the COVID-19 spending which has a bearing on energy has been steered towards decarbonization.

In the early months of the pandemic many were hopeful that it would provide an opportunity to reset behaviours and economic activity towards greener outcomes. So far, that has not proved to the be the case. Of the near USD 20 trillion in COVID-19 related spending, most has been allocated to emergency measures that lock in the dynamics of the pre-pandemic energy and manufacturing industries. Very little of the COVID-19 spending which has a bearing on energy has been steered towards decarbonization, although Europe has proved to be an exception. While comparatively marginal, this new spending on clean energy is contributing to slightly more non-fossil energy into our long-term forecast. It is nowhere near enough, however, to make the substantial breakthrough required for achievement of a net zero energy system by 2050, and thus we regard COVID-19 as a lost opportunity for accelerating the pace of the energy transition.

DEMAND

Buildings

The buildings sector will collectively consume 26% more energy in 2050 than in 2019, growing its share from 28% to one third of global energy use.

A growing, more prosperous population will result in a rapid expansion in floor space (both commercial and residential) of 62%. Space cooling will quadruple over the next three decades, driven by increases in standards of living and by climate change. Space heating demand on the other hand will reduce by 17%, owing to considerable efficiencies brought by electrification and heat pumps, which provide much more useful energy as heat than they consume as electricity. Energy demand from appliances and lighting will double – tracking slightly below GDP growth, due to moderate efficiency gains from the design of end use products. Other end uses such as cooking and water heating will stay relatively stable, as efficiency gains, particularly the shift to modern cooking methods, balance out any additional demand.

Buildings are currently responsible for 25% of energy-related emissions, including indirect emissions from electricity and direct heat production. By mid-century these emissions will decline in absolute terms by 44%, owing to cumulative efficiencies and a greener energy mix that includes substantially more electricity.

Manufacturing

Manufacturing energy demand, at 131 EJ in 2019, is forecast to grow by 8% by 2050. The economic output from production of base materials, construction, manufactured goods and mining will grow by 75%, indicating an efficiency improvement of 1.6%/yr.

The manufacturing sector had the largest share (30%) of final energy demand in 2019. The base materials subsector was responsible for 38% of manufacturing energy use. Manufactured goods was responsible for 31% of energy use, followed by iron and steel at 26%, and by construction and mining at 5%. Substantial energy-efficiency gains, including increased recycling, will balance the growth in demand for goods, such that goods manufacturing energy use will grow by 6% to 2033 and remain flat to 2050. The base materials sector will see initial growth to 2032, but reduce by a third thereafter to 2050, due to increased recycling and efficiency gains.

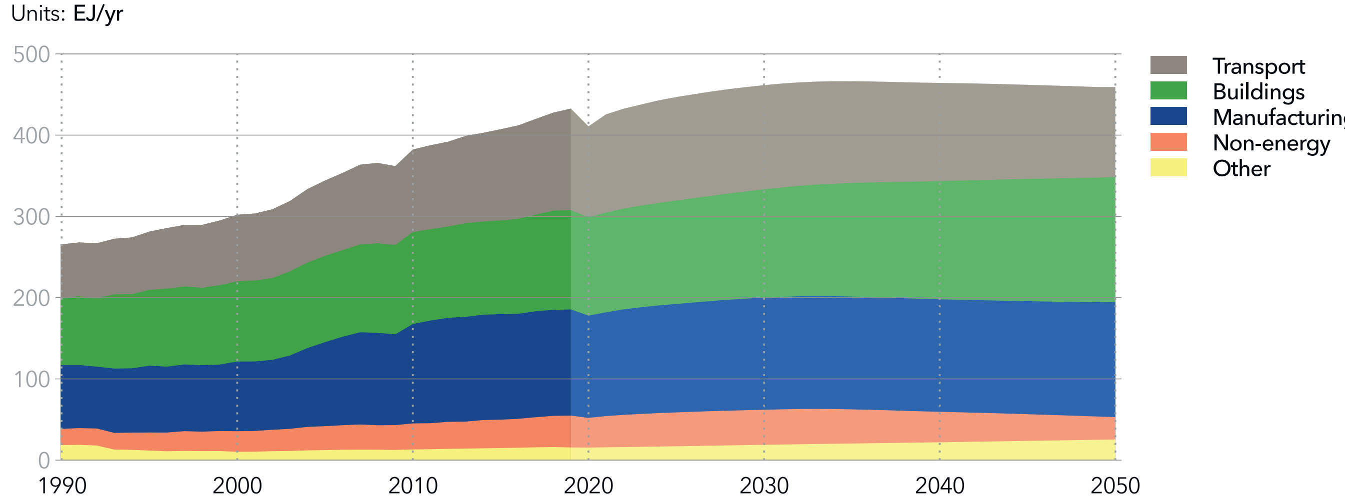
Manufacturing dominates demand sector emissions at 12 $GtCO_2$/yr (35% share). These will exactly halve over the forecast period owing to reduced coal use and a progressively greener electricity mix.

Energy use for heating purposes will see the largest efficiency gains towards 2050, due to changes in fuels and

FIGURE 12

World final energy demand by sector

Units: EJ/yr



Historical data source: IEA WEB (2020)

the more widespread use of heat pumps. With greater automation and digitalization, the machines, motors & appliances end-use will see its share of manufacturing energy demand increase to 32%, up from 24% in 2019.

Feedstock

In 2019, roughly 8% of global primary fossil-fuel supply was used for non-energy purposes, including 13% of oil. Petrochemicals are the largest consumer of feedstock and, of the consumption in this sector, about 45% was used to produce plastics in 2019, with the rest going to the manufacture of cosmetics, fertilizers, paints, and other chemicals. We expect that in 2050 the plastic proportion will have grown to about 61% of petrochemical feedstock demand.

While plastic demand continues to grow to 2050, reuse, substitution and especially recycling grows more rapidly – encouraged by taxes levied on unrecycled plastic. We estimate the global rate of plastic recycling will improve from around 13% in 2018 to 47% in 2050 as it is bolstered by more efficient (and potentially circular) chemical recycling, which supplements or replaces traditional, mechanical recycling. That is a major reason for non-energy feedstock use peaking in 2032 and then declining sharply towards 2050.

Transport

Efficiency gains and fuel switches – mainly to electricity and hydrogen – will result in transport energy demand falling from 125 EJ in 2019 to 111 EJ in 2050. Oil will supply just above half of this demand by mid-century, with electricity supplying a quarter, hydrogen 10%, and biofuels and natural gas 7% each. That is a very different picture from today, with transport at 29% of global final energy demand, almost entirely in the form of fossil fuels. 92% of road transport energy use is oil, with biofuels and natural gas taking 3% and 4% shares respectively and electricity 1%. The energy mix in aviation and maritime is fairly similar; only rail is supplied mainly by electricity.

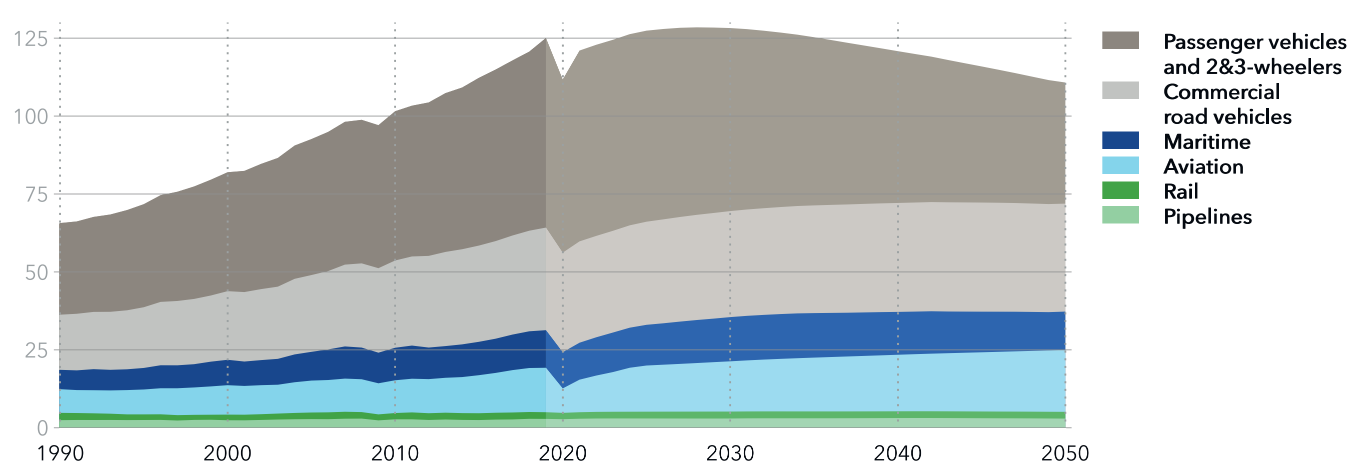
Transport services will grow significantly in the next 30 years: the passenger vehicle fleet will expand by two thirds reaching 2 billion units by 2050; aviation demand will recover from the pandemic – although not without effects on job travel – with global passenger flights growing 130% from 4.4 billion flights in 2019 to reach 10.2 billion flights in 2050; in the maritime industry, cargo tonne-miles will rise by nearly a third. Despite all this additional activity, transport energy demand will fall by 13% by 2050.

This counterintuitive development is mainly due to efficiency improvement associated with the electrification of road transport, supported by efficiency gains in

FIGURE 13

World transport sector energy demand by subsector

Units: **EJ/yr**



Historical data source: IEA WEB (2020)

DEMAND

aviation and maritime. By 2042, half of all passenger vehicles on the road will be electric.

Road transport

President Biden's recent fuel-efficiency plan includes a target that every other car sold in the US by 2030 will be an EV. Our forecast indicates that the goal is not farfetched and will be achieved by 2031 in the North America region. Indeed, Europe and Greater China will have already reached that milestone in 2027 and 2028 respectively.

Driving the surge in EV sales in those regions is a combination of factors, including a range of subsidies and other preferential treatments for owners. On the technology side, the average range of EVs is increasing, charging speeds are rising and charging infrastructure is expanding.

With better chemistries, manufacturing processes and pack designs, battery costs will keep plunging. By the middle of this decade, EVs will have demonstrably reached total cost of ownership (TCO) parity with internal combustion engine vehicles (ICEVs), and sales will rise dramatically but not uniformly across regions: uptake will be hampered by availability of electricity and infrastructure challenges, particularly in developing regions.

Commercial vehicles require much larger batteries, and we expect significantly higher and more-prolonged subsidy levels per vehicle in OECD regions and Greater China, where ICEVs will also be made less attractive through higher carbon prices.

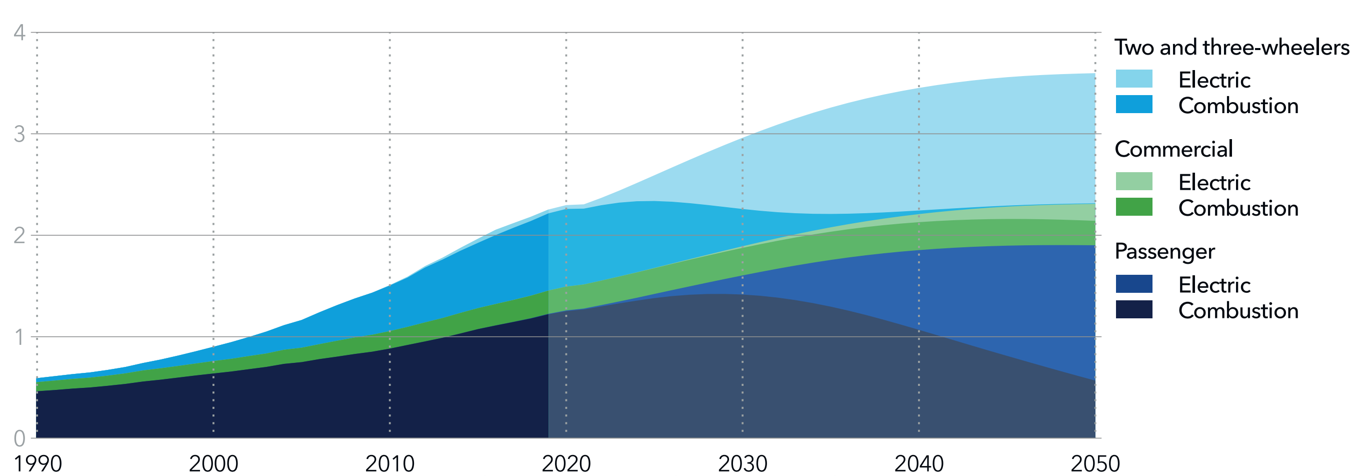
The rate of EV uptake will differ regionally, but in all regions the 50% of new sales figure will be reached before mid-century, and globally half of the passenger vehicle fleet will be electric by 2042. By 2050, they will consume just 36% of the road subsector's energy demand. Conversely, oil will still account for 60% of road transport energy, fueling just 30% of passenger and 59% of commercial vehicles, owing to the much lower efficiency of the combustion engine.

Some 16% of the commercial EV fleet in the OECD region and Greater China by 2050 will be fuel-cell electric vehicles (FCEVs). The combination of electricity, hydrogen and biofuel will chase 21 million barrels per day of oil out of the road transport energy mix by 2050 from its peak in 2019. In sum, our forecast indicates a rapid and significant electrification of all parts of road transport, in all regions.

FIGURE 14

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 (2021), IEA EV Outlook (2021), OICA (2016)

Maritime

Nearly 3% of the world's final energy demand, and 7% of the world's oil, is presently consumed by ships, mainly by international cargo shipping. By 2050, the dominance of oil in the fuel mix will have been displaced (42%) by low- and/or zero-carbon fuels like ammonia, hydrogen, and other electro-based fuels such as e-methanol. Natural gas – mostly LNG – will take a 39% share.

Driving this fundamental fuel switch are the IMO targets for a 50% absolute reduction in GHG emissions from 2008 to 2050. Our forecast assumes that a mixture of improved utilization and energy efficiencies, combined with a massive fuel decarbonization, will see this goal being met.

The digitalization of logistics and supply-chains will increase fleet efficiencies. However, in a world with GDP doubling, cargo transportation needs will outweigh efficiency improvements, and tonne-miles will increase by 32%. The exception is coal and oil transport, reducing by more than 50% and 20%, respectively, by 2050.

The energy density of batteries both today and in the future is likely to remain too low to play a larger role in deep-sea shipping. For further details on the fuel mix and use, refer to our *Maritime Forecast* companion report.

Aviation

Aviation consumes over 3% of the world's energy, almost entirely in the form of oil. By 2050, oil still accounts for 53% of aviation fuel, but in absolute terms oil use will be 26% lower than today. Following recovery from the pandemic demand slump, the number of flights will rise steadily in line with GDP growth to a level 140% higher in 2050 compared with 2019. Fuel use, however, increases by just 40% owing to efficiency gains in aircraft and engine technology and in logistics.

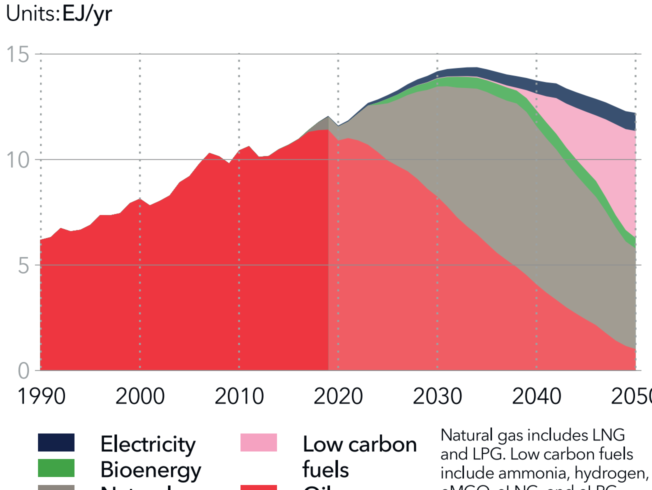
The three main options to replace oil-based fuel in aviation are: electricity, hydrogen and sustainable aviation fuel (SAF). All three are and will remain more expensive than oil-based fuels, and fuel and related technological changes are expected to be driven by regulatory and consumer-supported forces. Electricity, limited to the short-haul segment, takes just a 2% share of the aviation fuel mix in 2050. Cost, technology and regulatory challenges will see hydrogen-powered airplanes in use only after 2040 in the first few regions.

SAFs represent the most feasible decarbonization route, with biofuels reaching a 26% share of the aviation mix by 2050, and e-fuels (plus pure hydrogen) 19% - a pace of decarbonization running ahead of the CORSIA goals.

FIGURE 15

World maritime subsector energy demand by carrier

Units: EJ/yr

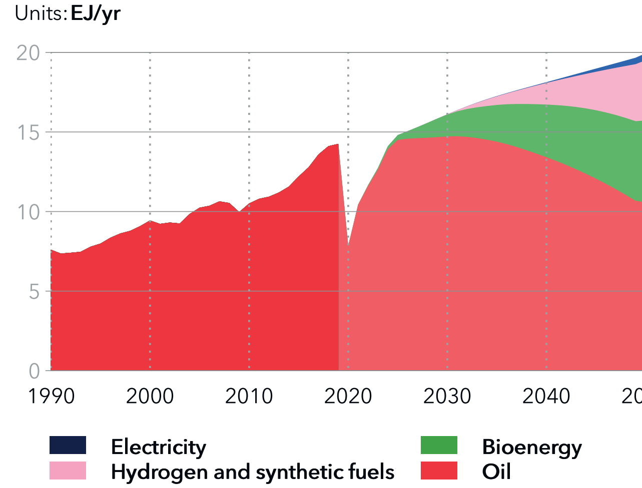


Historical data source: IEA WEB (2020)

FIGURE 16

World aviation subsector energy demand by carrier

Units: EJ/yr



Historical data source: IEA WEB (2020)

ENERGY CARRIERS

Electricity

Electrification is pivotal to the ongoing energy transition. Electricity demand will more than double between now and 2050, with the share of variable renewable energy sources (VRES) in the power mix growing from 8% today to reach 69% of power generation in 2050.

Growing at almost 3% per year to reach some 60,000 GWh in 2050, electricity demand will outpace economic growth despite continuous efficiency improvements. This is due to vast new categories of demand totaling 35,400 TWh/yr by 2050. Of this new demand, the electrification of road transport (2.8 billion EVs by 2050) is responsible for one fifth. Electrolysers producing green hydrogen will take a 23% share, new space cooling requirements 11%, and a similar share goes to the growing manufacturing subcategory of machines, motors & appliances.

Historically, prices have been set by the variable cost of the most-expensive generation technology, providing revenue for all generators. With the growing dominance of new technologies, including solar, wind, storage, and power-to-X, new rules will emerge. For example, in the 2050 power system, the maximum price arises when wind and solar supply are at their lowest, unlike the current power system where peak price would typically be at the time of maximum load.

Towards 2030, demand growth and an expansion of VRES will see a steady increase in grid investments, rising by between USD 150-200bn/yr from pre-pandemic levels. In terms of circuit-km, transmission lines will double and distribution lines more than double by 2050. Some 15% of grid investments will be steered towards digital infrastructure, to address the complexity of a more decentralized power system.

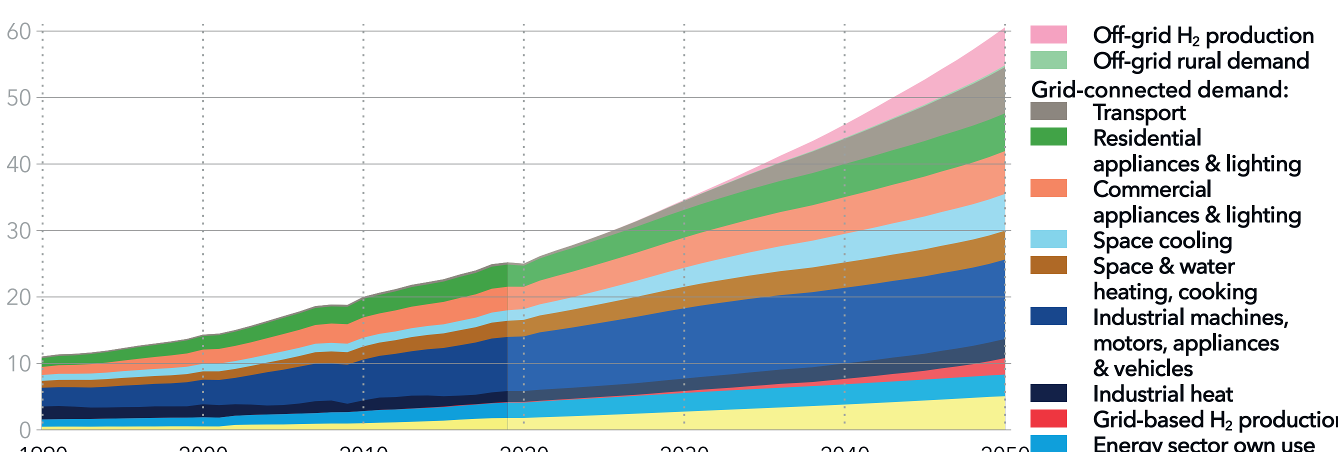
With rapid retirements from 2026 onwards, coal will fall to almost 75% of present capacity by 2050. With lower emissions and higher flexibility, gas remains competitive, with capacity reducing just 22% from current levels. Nuclear-power capacity will stay flat throughout the forecast horizon, with new capacity additions, largely in Greater China, compensating for retirements in Europe and North America. In relative terms, nuclear more than halves its share, dropping from 10% in 2019 to 4.3% in 2050. Hydropower will be limited by resource constraints, reducing its share in the global electricity mix from 16% in 2019 to 12% in mid-century.

In 2019, only 26% of electricity was supplied from renewable sources. By 2050 that share will have risen to 82%, along with major changes in flexibility and storage, which we address in the sections that follow.

FIGURE 17

World electricity demand by sector

Units: PWh/yr



Historical data source: IEA WEB (2020); IEA ETP (2016); Harvey (2014); Nakićenović et al (1996); EIA RECS (2015); Ürge-Vorsatz et al (2015)

Hydrogen

Hydrogen is a major contender for hard-to-abate sectors where electrification is either infeasible due to the low energy density of batteries or very costly. The production of hydrogen is, however, expensive and involves significant energy losses. Absent some extraordinary policy shift to subvent its production and use, we do not foresee hydrogen supplying more than 5% of global energy demand by 2050.

Synthetic fuels, such as e-methanol, e-ammonia, or sustainable aviation fuels, are all hydrogen-derivatives and are included in our total hydrogen demand forecast. By 2050, synthetic fuels will account for 70% of aviation's and virtually all of maritime's 'hydrogen' demand.

We forecast that, by 2050, hydrogen will have replaced fossil fuels in many industrial heat applications. Manufacturing will thus account for 32% of hydrogen demand. The next-heaviest user (17% share) of hydrogen (or rather hydrogen derivates) will be maritime, where few battery-electric options exist. One fifth of aviation fuel will be hydrogen based by 2050, equating to 11% of total hydrogen demand. Hydrogen will struggle to replace natural gas in buildings for space and water heating and cooking.

Although up to 10% of hydrogen can be blended into existing gas networks, pure hydrogen requires expensive network retrofitting and a total upgrade of appliances.

The leading method of hydrogen production is currently steam methane reforming (SMR) . However, fugitive emissions of methane in the production of the natural gas feedstock are controversial, and CO_2 emissions also have to be captured for the hydrogen to be considered 'blue'. Over time, blue hydrogen will steadily lose market share to green hydrogen produced via electrolysis, as the latter benefits from scale economies and the downward cost trajectory of VRES power.

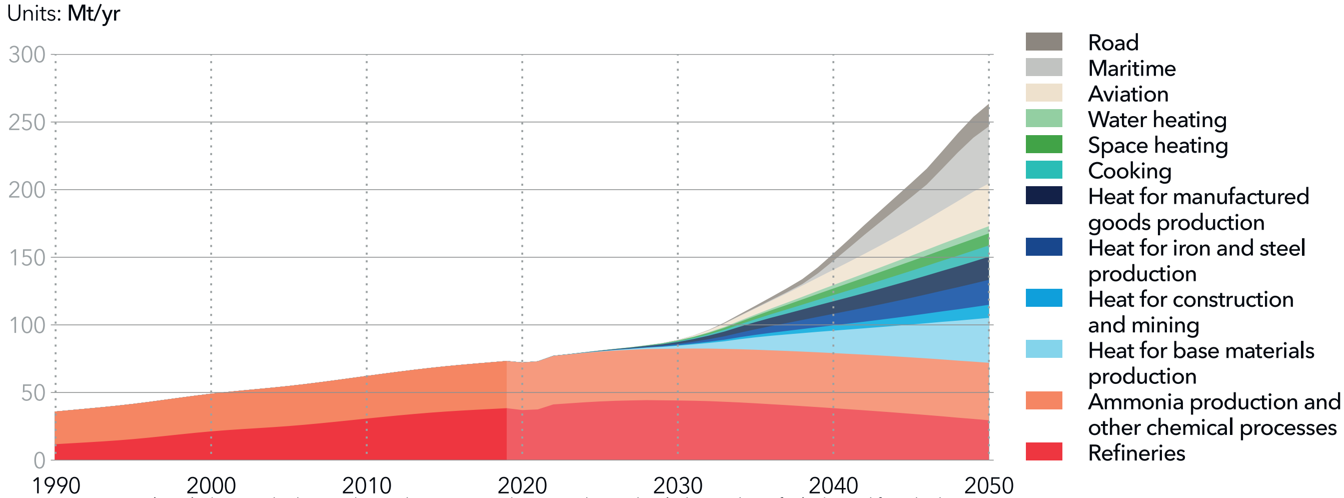
In our forecast, we distinguish further between grid-powered and off-grid electrolysis. In the former, operators will have to compete with many other takers for low-cost VRES electricity such as demand response, pumped hydro, EVs (storage), and utility-scale batteries. This limits annual operating hours to the extent that off-grid dedicated renewable generation for hydrogen production will become increasingly attractive.

By 2050, 61% of the the world's 281 Mt/yr hydrogen supply will come from electrolysis, split roughly equally between solar PV (16%), onshore wind (16%), offshore wind (11%), and grid-electricity (18%). Total installed electrolysis capacity will reach 3 TW by 2050.

FIGURE 18

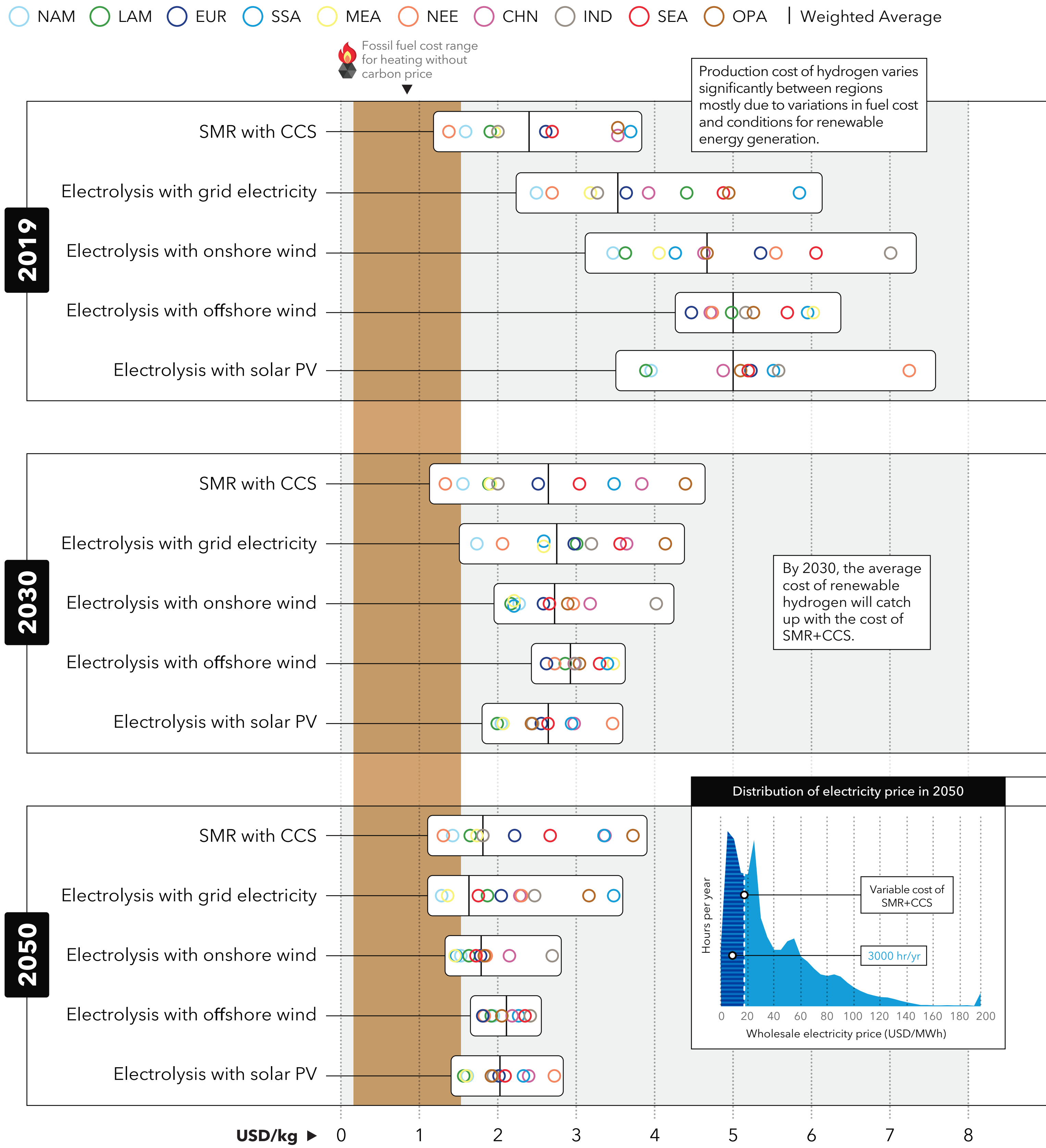
World hydrogen demand by sector

Units: Mt/yr

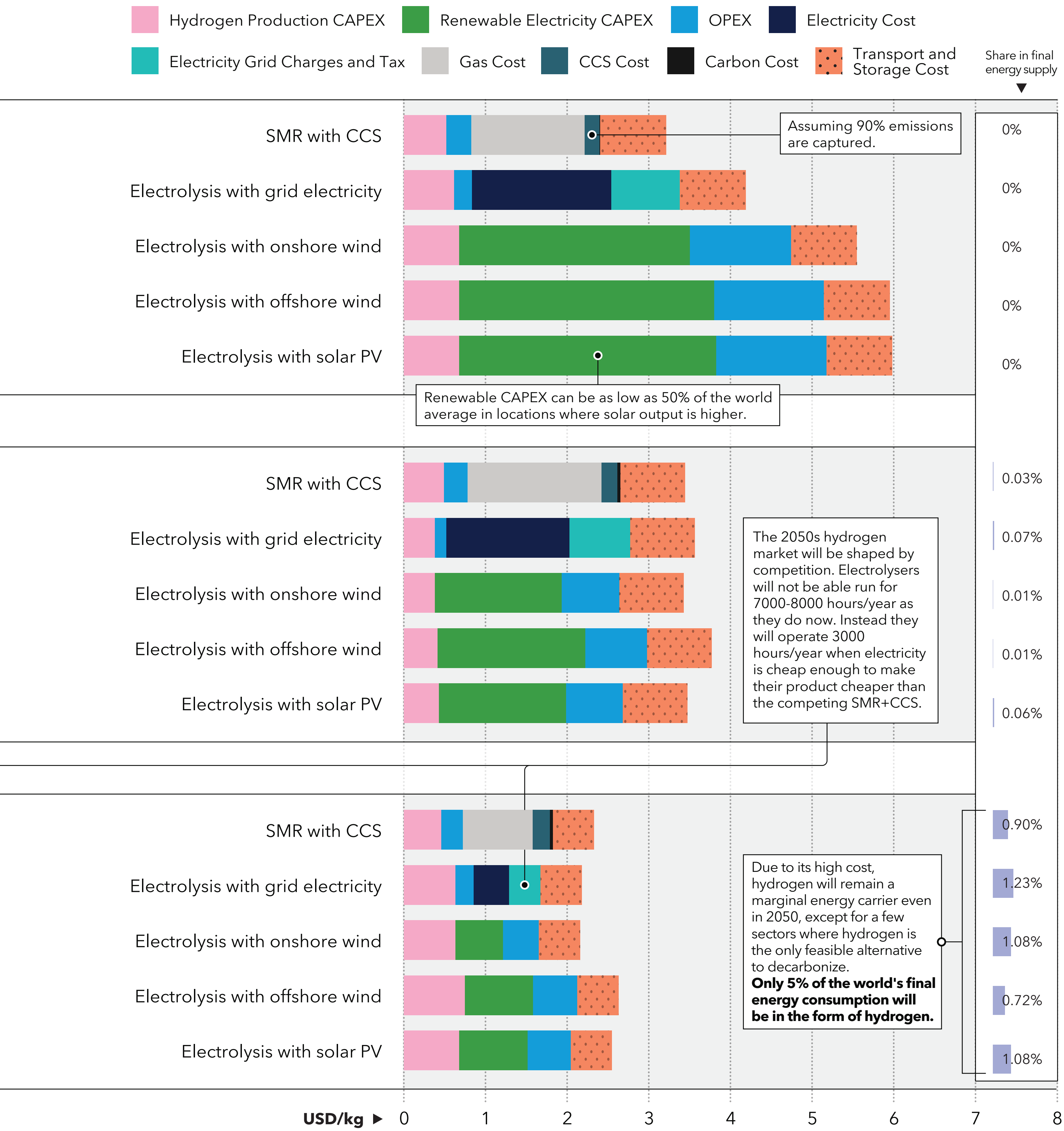


Only includes pure hydrogen demand. Maritime and aviation demand includes synthetic fuels derived from hydrogen.
Historical data source: IEA Future of Hydrogen (2019)

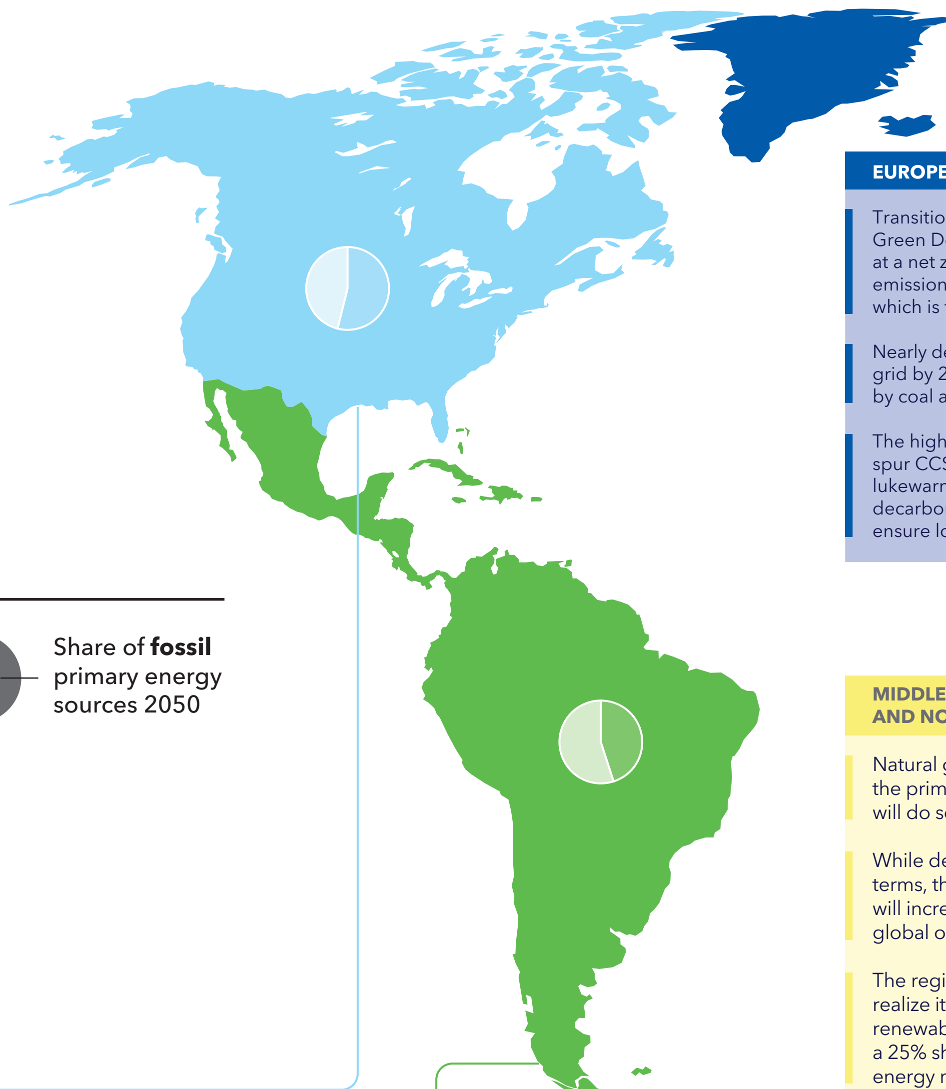
LEVELIZED COST OF HYDROGEN PRODUCTION



COST COMPONENTS OF HYDROGEN

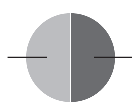


WE ANALYSE 10 GLOBAL REGIONS



KEY

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



Share of **fossil** primary energy sources 2050

EUROPE

- Transition policies, European Green Deal and 'Fit for 55' aim at a net zero greenhouse gas emission economy by 2050, which is forecast not to be met
- Nearly decarbonized electricity grid by 2050; < 5% generation by coal and natural gas
- The high carbon price could spur CCS uptake, but lukewarm support and a decarbonized power system ensure low implementation

MIDDLE EAST AND NORTH AFRICA

- Natural gas and oil dominate the primary energy mix and will do so until 2050
- While declining in absolute terms, this region's cheap oil will increasingly dominate global oil production.
- The region will start to realize its vast potential for renewable energy, reaching a 25% share in primary energy mix in 2050

NORTH AMERICA

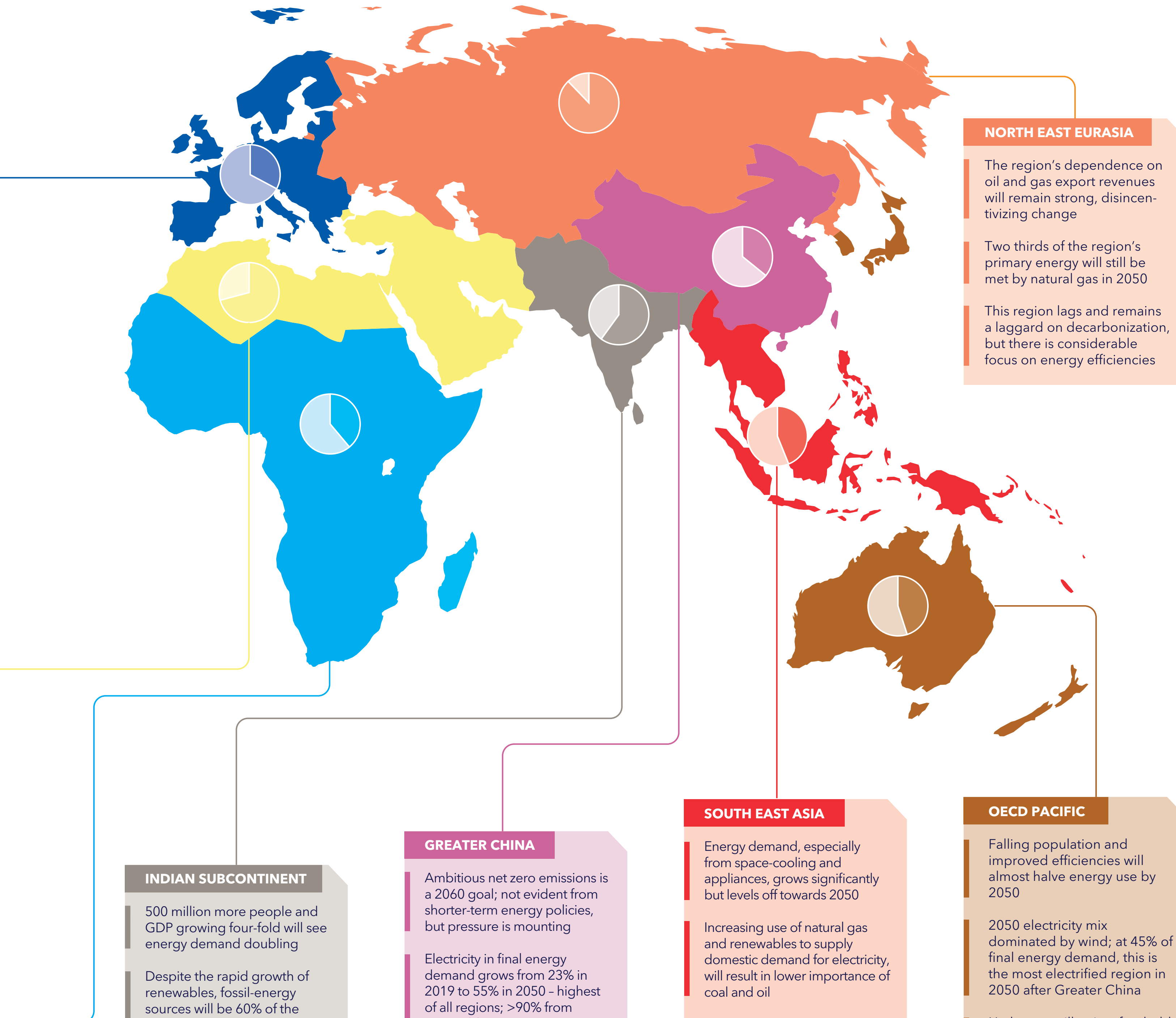
- Decarbonizing electricity by 2035, part of the 'Build Back Better' plan, is ambitious but unlikely to be met
- A massive buildout of grids is forecast to bring aboard renewables; 55% of generation in 2030 and 75% by 2050
- The switch to passenger EVs is slow but gaining momentum, and contributes to declining oil use

LATIN AMERICA

- Hydrogen from dedicated, low LCOE solar PV may change the region's energy landscape
- Power generation mix will switch from hydropower/natural gas/fuel oil to hydropower/solar/wind
- Renewables > 50% of 2050 primary energy mix; bioenergy above 20%

SUB-SAHARAN AFRICA

- Least-developed and least-electrified world region; only 42% of its people currently have access to electricity
- Soaring energy demand from a growing population and economy will be counteracted by efficiencies, e.g. traditional biomass cooking replacement by gas and electricity
- Off-grid solar PV plays a significant role in energy access, and with grid-connected solar, accounts for almost 40% of power generation in 2050



NORTH EAST EURASIA

The region's dependence on oil and gas export revenues will remain strong, disincentivizing change

Two thirds of the region's primary energy will still be met by natural gas in 2050

This region lags and remains a laggard on decarbonization, but there is considerable focus on energy efficiencies

INDIAN SUBCONTINENT

500 million more people and GDP growing four-fold will see energy demand doubling

Despite the rapid growth of renewables, fossil-energy sources will be 60% of the energy mix in 2050

Electricity's share in building energy demand will triple by 2050, enabling universal access to electricity

GREATER CHINA

Ambitious net zero emissions is a 2060 goal; not evident from shorter-term energy policies, but pressure is mounting

Electricity in final energy demand grows from 23% in 2019 to 55% in 2050 – highest of all regions; >90% from renewable sources

Peak coal already achieved. Share of coal in power mix (currently 60%) reduces to 5% over the forecast period

SOUTH EAST ASIA

Energy demand, especially from space-cooling and appliances, grows significantly but levels off towards 2050

Increasing use of natural gas and renewables to supply domestic demand for electricity, will result in lower importance of coal and oil

Manufactured goods production more than doubles by 2050, driving demand for gas and transforming this region into a net-importer of LNG

OECD PACIFIC

Falling population and improved efficiencies will almost halve energy use by 2050

2050 electricity mix dominated by wind; at 45% of final energy demand, this is the most electrified region in 2050 after Greater China

Hydrogen will gain a foothold (9% of energy use), sourced initially from Australia through SMR processes, but later mainly via renewably powered electrolysis

SUPPLY

Hydrocarbon decline

Coal – coal demand peaked in 2014 at 7.9 billion tons. Since then, it has been losing ground to natural gas and renewables in Europe and North America. Coal use in Greater China will decline significantly after 2030. Strong growth in the Indian Subcontinent and South East Asia will level off by then, and with coal exiting the energy mix elsewhere, except for high-heat processes in industry, its use will decline to just above a third of current levels by 2050.

Oil – global oil demand may have peaked in 2019, but post-pandemic recovery could see a new all-time high. Our forecast demand for 2019 and 2025 differs by just 1%. From that point oil use reduces slowly towards 2030, but then the decline steepens by an average -2.8%/yr over the following two decades – much faster than the average growth of 1% per year we have seen in the past. Oil falls most sharply in the transport sector, halving over the next 30 years due to electrification of road transport and the rising use of low- and zero-emission fuels in aviation and maritime after 2030. Oil use in petrochemicals will reduce after 2035 due to recycling and bio-derived feedstock. Globally, oil use declines 45% to 2050 compared with 2019, with production concentrated ever more strongly in Middle East and North Africa.

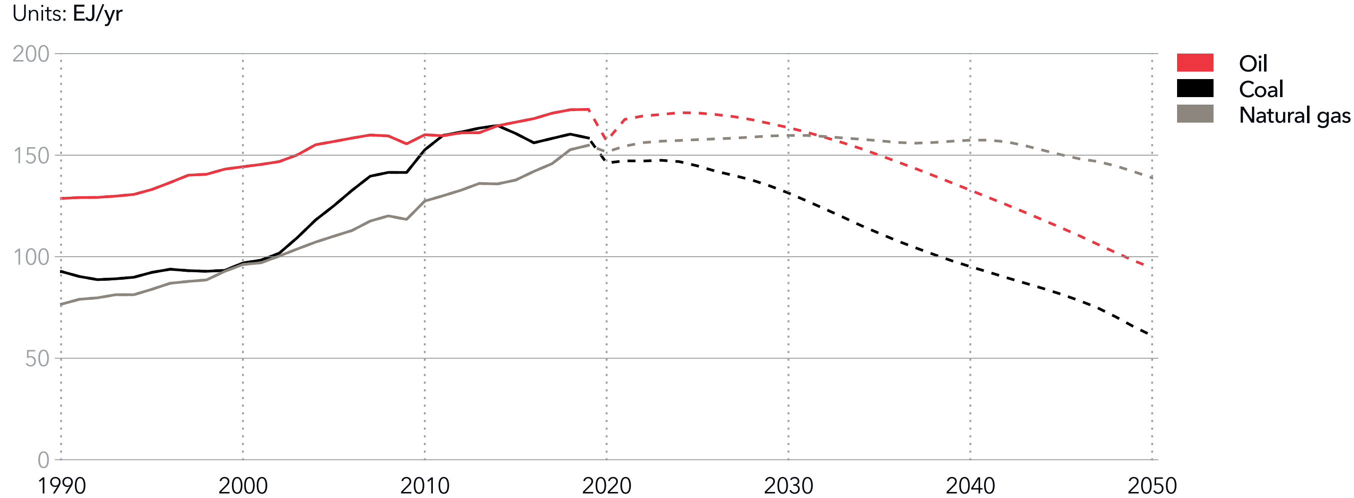
Natural gas – overtakes oil as the largest source of primary energy in 2032 and holds the top spot throughout our forecast period. Natural gas use will grow slowly this decade, have a flat development in the 2030s, and thereafter taper off by some 10% to 2050. Demand changes will differ regionally: in OECD countries, gas consumption will gradually decline; in Greater China, it will peak in the early 2030s; in the Indian Subcontinent, demand will almost triple by mid-century. Almost half the demand for gas derives from its final use in buildings, transport and manufacturing. The other half involves transformation into other uses: electricity, petrochemicals and hydrogen production.

The LNG share of total gas export will grow throughout the forecast period. The big producers are also the big exporters, and North America – which is distant from its gas customers – will see the largest growth in liquefaction, accounting for 38% of global capacity by 2050. By 2050, just 15% of gas will be carbon free, led by regions with higher decarbonization ambitions and higher carbon prices: Europe, Greater China, North America, and OECD Pacific. Hydrogen will grow to supply 3.5% of gas demand, with CCS in power and industry and biomethane making up the balance of 'carbon free' gas.

FIGURE 19

World primary fossil fuel supply by source

Units: EJ/yr



Historical data source: IEA WEB (2020)

Wind

Wind power provided 5% of the world's electricity output in 2019, almost exclusively in the form of onshore wind. By mid-century that share will rise to 33% as electricity generation from wind increases from 1,420 TWh/yr in 2019 to 19,000 TWh/yr in 2050.

Onshore wind installation will increase 8-fold by 2050 as it outcompetes fossil sources on cost from the current decade onwards. By the 2040s, it also gains advantage over solar because wind turbines generate electricity when prices are high more often than PV. For offshore wind, we expect strengthened support in developed countries to bypass community opposition to onshore turbines. The share of offshore wind in total wind electricity generation will increase steadily, rising globally from 6% in 2019 to 40% in 2050. However, by 2050, only Europe and OECD Pacific will have more offshore than onshore wind.

With new turbine types and continued increases in turbine, blade, and tower sizes, capacity factors will improve, raising the world average for onshore wind turbines from 21.5% in 2019 to 31% by 2050. For offshore wind turbines, where wind conditions are more favourable, the average capacity factor is already 34%. We expect this to rise to 50% by 2050.

Cost reduction in onshore wind will total 42% over the period 2020 to 2050, driven by rising capacity factors and cheaper turbines. Cost reductions for the less-mature segments will be even steeper. For fixed and floating offshore wind levelized costs will fall 44% and 80% respectively, boosted by improvements in operating and maintenance expenses as experience in installing and operating offshore wind turbines builds.

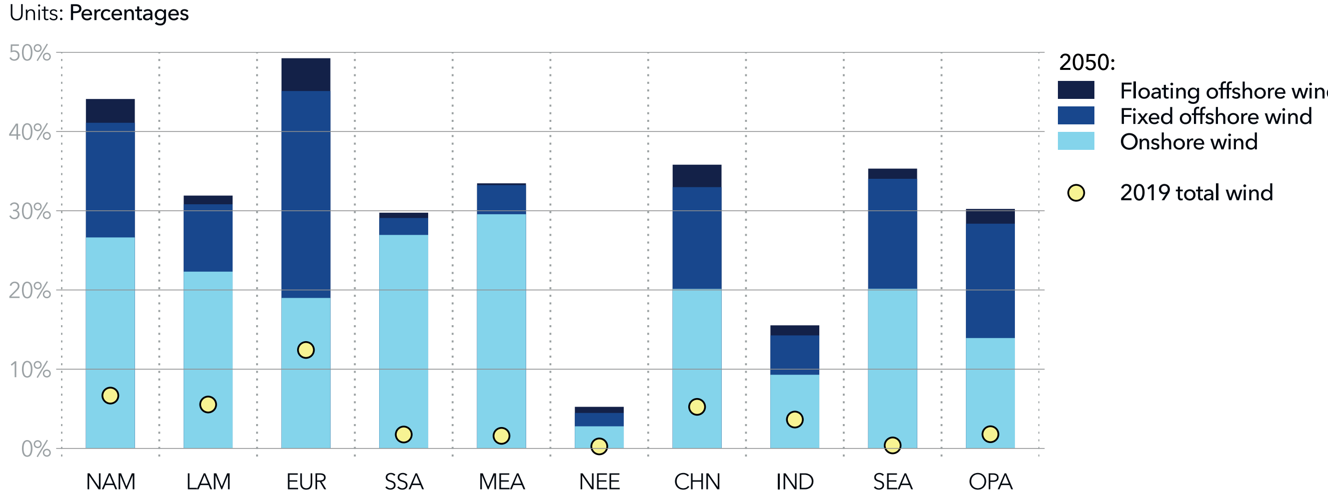
Global wind capacity additions will increase from 60 GW/yr in 2019 towards 340 GW/yr by mid-century, with marked differences in regional developments as illustrated in Figure 20 below.

Installed capacity reached 709 GW at the beginning of 2020. We forecast 1 TW in 2022, 2 TW in 2029, 4 TW in 2043, and 5.9 TW in 2050, of which 1.7 TW will be offshore. These developments are linked to larger turbines, mega-sized projects, and a more dedicated offshore supply chain. In addition, the 2020s will see floating wind progress to full-scale demonstration projects and on to commercial-scale deployments. We predict that floating offshore wind projects will have 264 GW of installed capacity by 2050.

FIGURE 20

Share of wind in electricity generation by region

Units: Percentages



Historical data source: IEA WEB (2020)

Solar PV

Grid-connected solar PV electricity will grow from 3.2% of global grid electricity generation in 2019 to 36% by 2050. Installed capacity increases 20-fold over the next 30 years to reach 11.5 TW in 2050. Greater China will hold a 35% share of this capacity, followed by the Indian Subcontinent at 20%.

In 2020, despite the supply-chain disruptions caused by the pandemic, new solar PV installations again set a record at 129 GW. From 2030 onwards, we expect annual additions of between 300 and 500 GW.

A high cost-learning rate for solar panels (26%, declining to 17% by 2050) for every doubling of installed capacity and rising capacity factors (improving from 19% today to 26% in 2050) will see solar PV costs continue to fall, as illustrated below (Figure 21). Currently, the global weighted average levelized cost of energy (LCOE) for solar PV is breaking the USD 50/MWh barrier, with individual project costs well below USD 20/MWh in locations like the Middle East and North Africa and Latin America.

Cost leadership is a necessary but not sufficient condition for the expansion of solar PV. That is because, from a value perspective, solar can become a victim of its own success. Typically, as the share of solar PV in a grid grows, it captures progressively lower prices for daytime production.

Lower received prices will not, however, be a showstopper for the strong growth of PV generation. Increasingly, PV and storage systems are designed as a 'package' that can produce energy on demand, just like hydropower, nuclear or combustion power plants. Solar PV + storage is thus a distinct power station category.

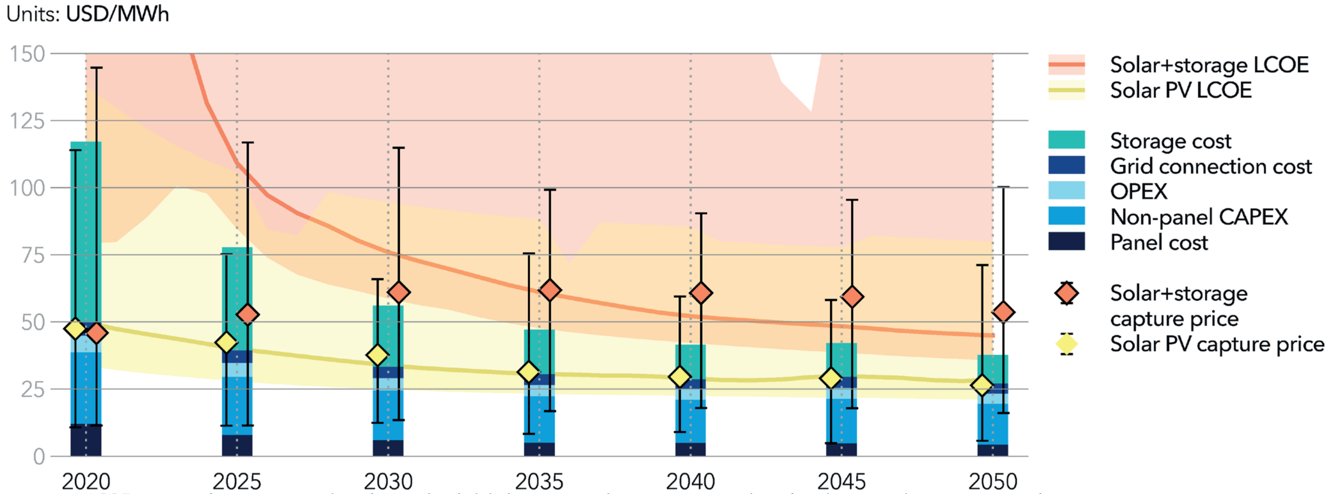
The levelized cost of solar + storage is currently more than double that of solar PV without storage. However, with a continued drop in battery prices, the gap between the two will narrow to below 65% by 2030. By then, the capture price advantage of solar + storage over regular solar PV plants will surpass the cost disadvantage on a globally averaged basis. Within a decade, about a quarter of all PV installed will be with dedicated storage, and by mid-century this share will have risen to half. In 2050, total installed capacity will be 7.6 TW for solar PV and 3.9 TW for PV + storage.

Total installed off-grid solar PV capacity for hydrogen production will be around 800 GW by 2050. By then, a further 130 GW of off-grid solar PV, coupled with inexpensive battery storage, will be providing hundreds of millions of less-affluent people in the Indian Subcontinent and Sub-Saharan Africa regions with access to energy.

FIGURE 21

Global solar levelized cost of energy (LCOE) and capture price, with spread over regions

Units: USD/MWh



LCOE curves and capture prices show the weighted global averages at the investment year, based on the regional average expected capacity factors. Discount rates are 7-8%/yr. Error bars show the spread across 10 regions. Individual projects may lie outside these ranges.

Storage and flexibility

As we move towards a decarbonized electricity system, there is both opportunity and need for flexibility. With high shares of solar and wind, traditional sources of flexibility will need to be accompanied by a large amount of storage. Over the next 30 years, utility-scale storage capacity will grow 160% to reach 7.3 TWh (Figure 23).

With the value of flexibility increasing, many conventional generation technologies, like gas-fired power stations, will seek ways to accelerate their ramp rates and reduce their start times. There will be a growing emphasis on shifting electricity usage from peak periods to times of lower demand. Better prediction of renewable power generation – and also consumption – levels will evolve, and new technologies and market mechanisms will allow more consumers to provide flexibility in the form of demand response.

Converting cheap electricity from VRES to other energy carriers, such as hydrogen, will add more flexibility. Adoption of smart meters and smart grids, continued investment in the interconnectors between physical transmission systems, and in the links between generation and load centres, will also contribute towards better utilization of excess renewable supply.

Storage technologies will increasingly allow power generation to be decoupled timewise from power demand. Storage in today's power system is mostly in the form of pumped hydro. Although it is a mature technology and limited by geography, pumped hydro is set to grow by 20% over the next three decades.

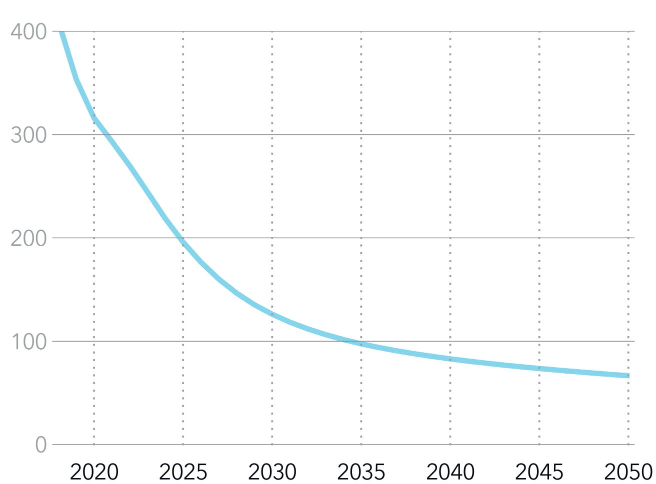
High penetration of wind and solar raises price variability and strengthens the business case for storage, as does the plunging cost of battery technology (Figure 22). We forecast widespread expansion of battery storage, dominated by Li-ion batteries with 2-4 hours capacity. From 2040 onwards, throughput of vehicle-to-grid systems in the world will be almost as large as that of dedicated Li-ion batteries and pumped hydro, reaching 240 TWh/yr globally by mid-century.

In larger markets for utility-scale battery storage (e.g., China, South Korea, Japan, US), demand for longer-duration storage (> 5 hours) is already developing and will intensify. This trend will boost new technologies like vanadium redox flow batteries, zinc-based chemistries, or compressed air. Long-duration storage capacity is likely to be nearing 1 TWh by 2050.

FIGURE 22

Utility-scale Li-ion battery system cost

Units: USD/kWh

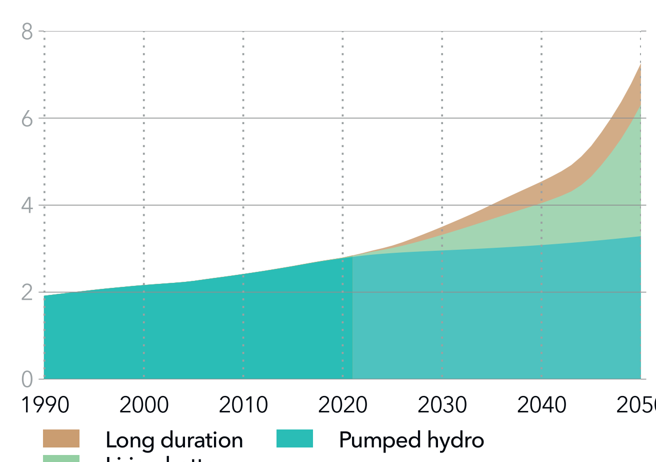


Historical data source: NREL (2020)

FIGURE 23

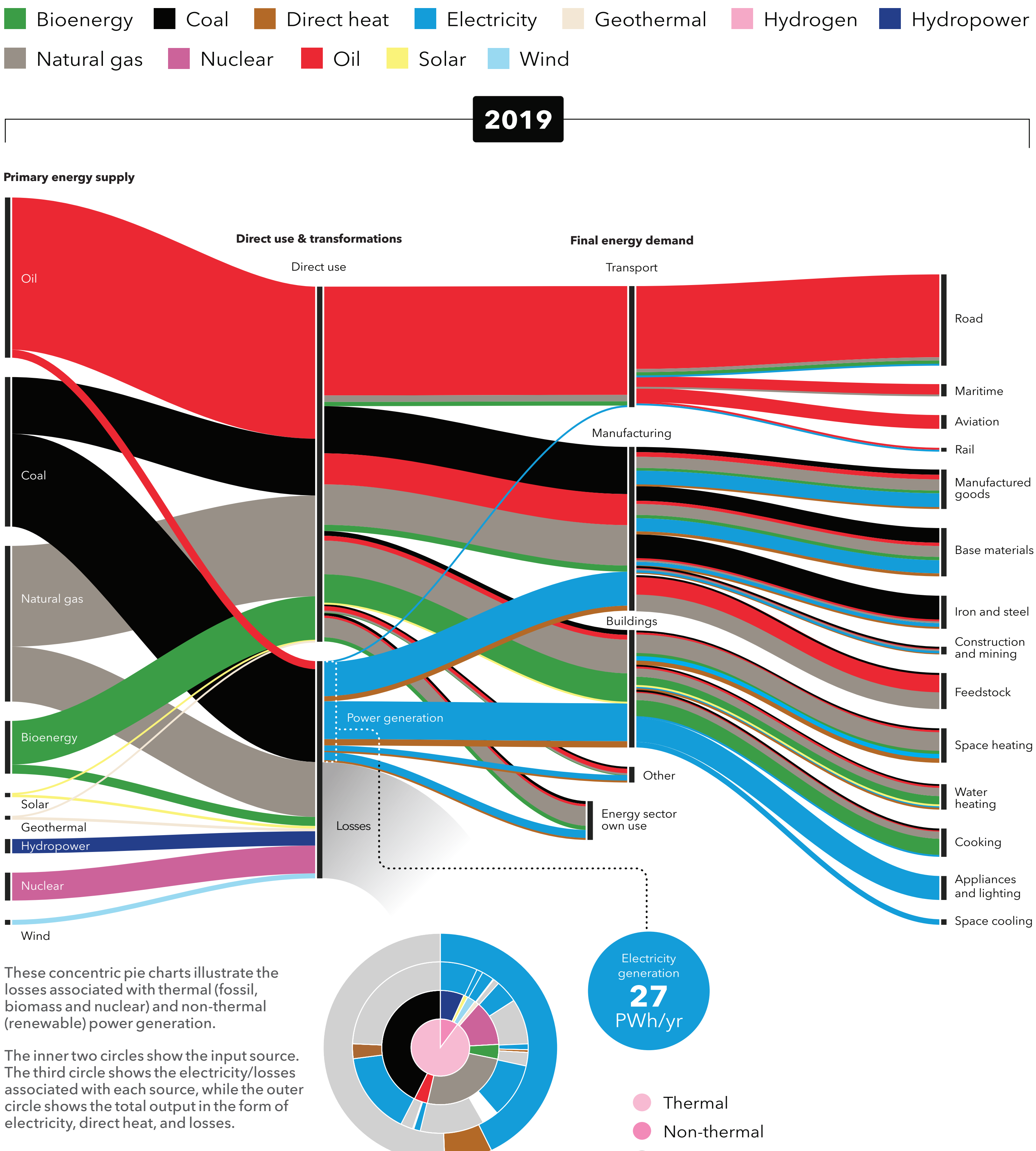
World utility-scale energy storage capacity

Units: TWh



Historical data source: GlobalData (2021), US DOE (2021)

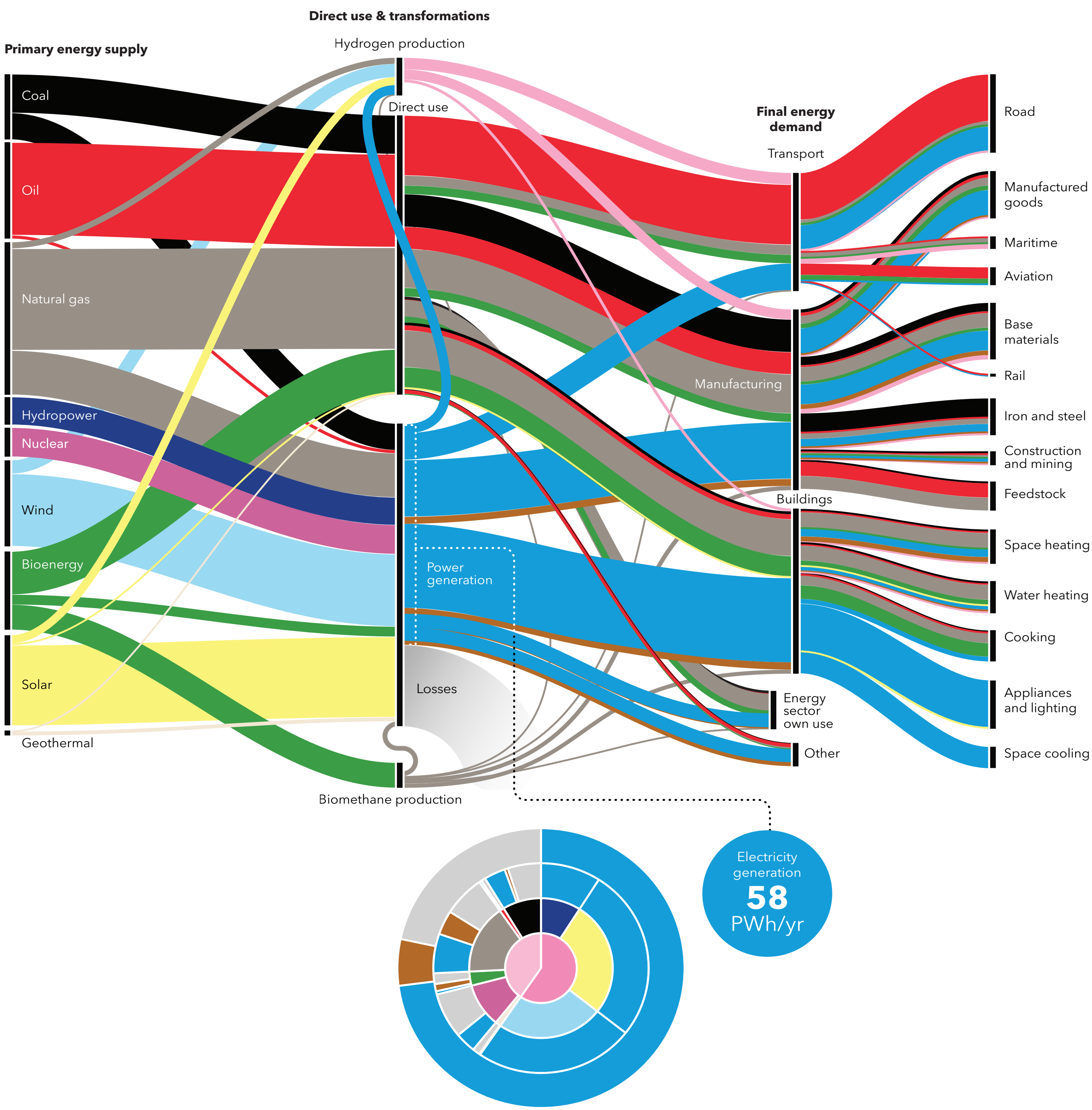
COMPARISON OF ENERGY FLOWS: 2019 AND 2050



These concentric pie charts illustrate the losses associated with thermal (fossil, biomass and nuclear) and non-thermal (renewable) power generation.

The inner two circles show the input source. The third circle shows the electricity/losses associated with each source, while the outer circle shows the total output in the form of electricity, direct heat, and losses.

2050



Direct use & transformations
Primary energy supply
Hydrogen production
Coal
Direct use
Oil
Natural gas
Hydropower
Nuclear
Wind
Bioenergy
Solar
Geothermal
Power generation
Losses
Biomethane production
Final energy demand
Transport
Manufacturing
Buildings
Energy sector own use
Other
Road
Manufactured goods
Maritime
Aviation
Base materials
Rail
Iron and steel
Construction and mining
Feedstock
Space heating
Water heating
Cooking
Appliances and lighting
Space cooling
Electricity generation
58
PWh/yr

EFFICIENCIES AND EXPENDITURE

Energy efficiency

Accelerating efficiencies in the production and use of energy are pivotal to the energy transition.

Globally, energy intensity (unit of energy per dollar of GDP) has been reducing by 1.7%/yr on average for the last two decades. This decline has not been smooth, and the COVID-19 pandemic introduced further short-term spikes with varying fluctuations in both energy consumption and GDP.

Irrespective of short-term impacts of the pandemic, energy intensity will continue to decline faster than in previous decades, by 2.4%/yr on average over the next 30 years (Figure 24). The cumulative effect is that energy intensity will drop from 4.3 MJ/ USD in 2019 to 2.0 MJ/ USD in 2050. In other words, by mid-century we will use less than half of the energy used today to produce one dollar of GDP.

From an energy production perspective, 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 assumed to be 100% efficient by the conventions of the energy-accounting method we use. Therefore, 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. The obvious example is the electrification of road transport, where EVs are more than three times more efficient than their fossil counterparts.

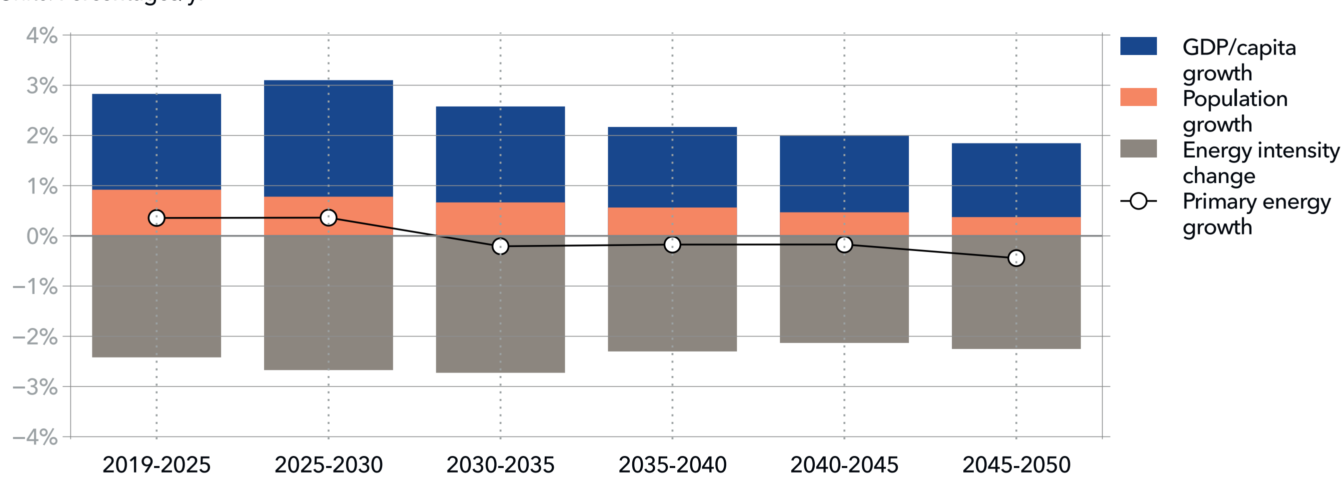
In calculating sectoral efficiencies, we take a range of activity, technological and structural changes into account in addition to electrification. For example, technology improvements resulting in better engine performance, hull hydrodynamics or insulation. We find that without expected efficiency gains in transport, buildings, and manufacturing, energy demand would be 65% higher than we forecast for 2050.

There is considerable potential to accelerate efficiencies beyond our forecast. That, however, will require new mandates from governments and international bodies that we are as yet not able to forecast, along with unprecedented co-operation within industries on new standards and recommended practices.

FIGURE 24

World energy intensity and annual reduction rate

Units: Percentages/yr



Energy expenditure

The energy transition that we forecast is not only affordable but leads to considerable savings at the global level.

Renewables, storage and grid buildouts, will indeed require very large upfront investment; this is why some believe that the transition is 'unaffordable'. Our results suggest the exact opposite: whereas global GDP will more than double by 2050, global energy expenditures do not increase very much from today's levels. This is thanks to improvements in energy efficiency and in renewable-energy technologies.

World energy expenditures will shift from fossil to non-fossil sources, and the annual sum expended will increase by only 4%, from USD 4.5trn in 2019 to USD 4.7trn in 2050 The fossil-energy share will decline by more than a third of today's 76%, dropping to 42% by mid-century.

There are various definitions of 'energy expenditure', and we use a strictly stipulated terminology. However, we have excluded investments in energy-efficiency measures, as well as in downstream carbon-mitigation costs. Nor do we incorporate costs related to end-use spending (in manufacturing, transport, etc.).

Upstream oil and gas expenditures will decline by 46% through to 2050. Oil investments will drop, while gas investment will remain constant before slightly decreasing in the 2040s. On the other hand, given the long lifetimes of installed capacity, operating expenses will remain quite high, only decreasing by 35% for oil and remaining flat for gas.

Fossil fuel-fired power investments will decline spectacularly by 96% over this same period, to a mere USD 5bn. Operating and maintenance of fossil power stations (excluding fuel) will remain at around USD 350bn due to the inertia of long-lifespan installations.

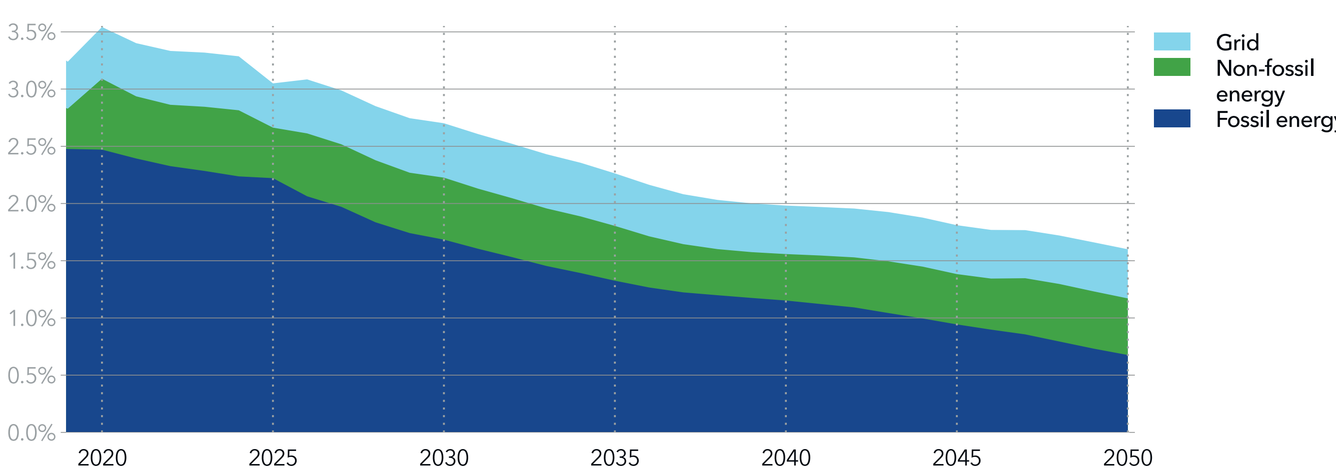
The increase in electricity demand will lead to an almost doubling of non-fossil power expenditures by 2050. The rise is particularly visible for solar PV and wind power. Together, they will represent a fifth of global energy expenditures in 2050, an almost four-fold increase compared with 2019.

The bottom line however is that the share of GDP devoted to energy worldwide will halve within the space of a single generation. Conceptually, these 'savings', amounting to tens of trillions of dollars per decade, could be applied to accelerating the transition.

FIGURE 25

World energy expenditure as a fraction of world GDP

Units: Percentages



NOT FAST ENOUGH

The latest science is clear on the need to achieve net zero emissions by mid-century if we are to reach the ambitions of the Paris Agreement. For that to occur, we must drive down emissions from human activities to as close to zero as possible by 2050. The energy-related emissions we forecast are very far from zero by 2050, and, together with other emissions from human activity, suggest a warming of 2.3°C by 2100 – a level considered dangerous by the scientific community.

Emissions

Energy production and use represents 70% of global GHG emissions, of which most is CO_2. We forecast that annual energy-related CO_2 emissions in 2050 will be at 19 Gt, a 45% reduction compared to the present level.

50% of energy-related emissions have been added to the atmosphere in the last 50 years. After staying virtually flat between 2014-2016, global energy-related CO_2 emissions grew to reach a peak of 34.3 Gt CO_2 in 2019.

The effects of COVID-19 resulted in emissions dropping by approximately 6% in 2020. But as economic activity is now picking up, energy use and emissions are rising again. Energy-related emissions will climb back up 3% during 2021 and grow to 33 Gt CO_2 by 2023 before declining gradually to 31 Gt CO_2 in 2030, a level only 9% lower than 2019.

Combustion emissions currently come mainly from coal and oil use, but within the next three decades emissions will be increasingly dominated by natural gas. We forecast that emissions from coal will fall 62% by 2050, emissions from oil will halve, whereas emissions from natural gas will grow towards 2030 and then drop back to a level only 15% below today's emissions.

The main demand sectors of manufacturing, buildings and transport will all see emissions fall between 40 to 50% by 2050 due to the rise of renewably powered electricity and ongoing efficiencies described on page 28.

Regions

Absolute emissions will increase in the Indian Subcontinent and Sub-Saharan Africa to 2050. The highest-emitting region, Greater China, will reach peak emissions before 2030; emissions will then decline by 75% from today's levels. All other regions will reduce their emissions, with OECD Pacific, together with Europe, experiencing the biggest relative change. North East Eurasia will have the highest emissions per capita at 7.5 tonnes/person in 2050, followed by North America and Middle East & North Africa at 3.5 tonnes/person.

Carbon capture

CCS uptake will be very limited in the near- to medium-term, and effectively too late and minimal in the longer term. It is only in the 2040s, when carbon prices start to approach the cost of CCS, that deployment begins at scale. By 2050, total carbon capture will amount to just 6% of all annual energy-related emissions.

Overshooting the carbon budget

To limit global warming to below 1.5°C, the IPCC concludes that we have to limit cumulative emissions to 400 Gt CO_2 from the start of 2020 and into the future, and 1150 Gt CO_2 to stay below 2.0°C.

Using the IPCC carbon budgets and the aggregated CO_2 emissions from our forecast, we find that the 1.5°C budget will be exhausted in 2029. To exhaust the budget associated with the 2.0°C threshold it takes a further 24 years until 2053.

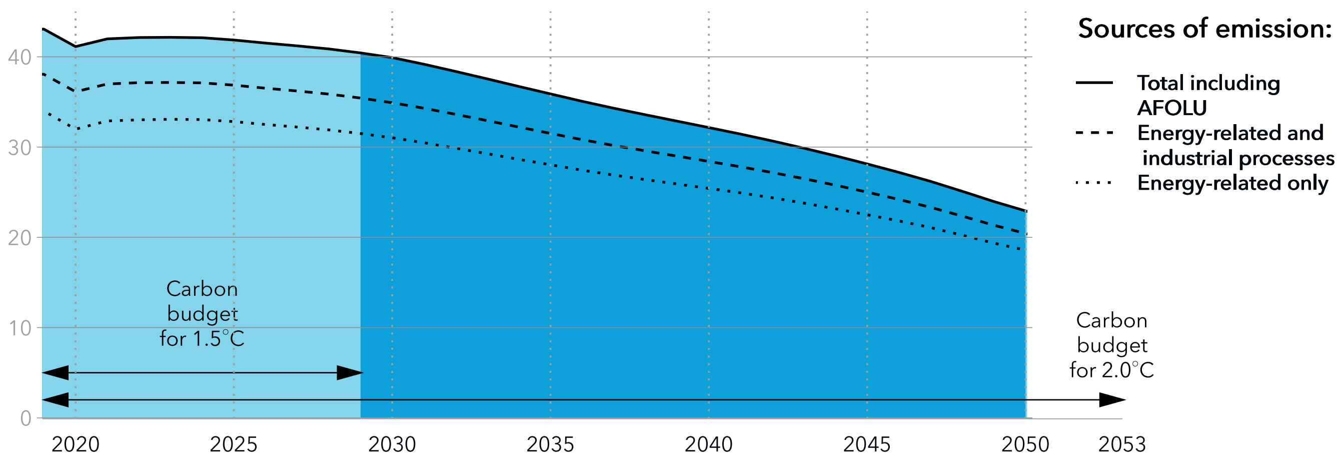
In arriving at these estimates, we add emissions from non-energy sources (e.g. agriculture and industrial processes) to give a full picture of CO_2 emissions from human activity.

To estimate the CO_2 emissions and global warming by the end of the century, we extrapolate the development of emissions and their capture towards 2100. The updated climate response from IPCC AR6 (IPCC, 2021) suggests that, with a likely budget overshoot of 370 Gt CO_2, the world will reach a level of warming of 2.3°C above pre-industrial levels by 2100.

FIGURE 26

Carbon emissions and carbon budget

Units: $GtCO_2$/yr



IPCC Sixth Assessment Report on climate science

The United Nations' Intergovernmental Panel on Climate Change (IPCC) published the first part of its Sixth Assessment Report (AR6) on 9th August 2021.

The report concludes that almost all emissions scenarios expect to result in 1.5°C of warming, "in the early 2030s". Without reaching "net zero" CO_2 emissions, as well as an immediate, sharp reduction in emissions of both CO_2 and other greenhouse gases – the climate system will continue to warm.

A key enhancement in AR6 is that its warming projections are based "for the first time" on multiple lines of evidence, including observations of historical and recent warming trends. This is a major shift, as earlier IPCC projections were based entirely on climate models.

The report also describes significant effects of the climate changing in areas such as rainfall patterns, the melting of icesheets and glaciers, permafrost and seasonal snow cover, and rising sea levels.

> "Today's IPCC Working Group 1 Report is a **code red** for humanity.

António Guterres

United Nations Secretary-General

9 August 2021

MODEL INPUT

Population

The number of people in the world is a central input to any energy forecast. The UN's World Population Prospects is the most widely used resource by energy forecasters.

However, the UN has been criticized for not paying enough attention to country-specific education levels – data that are relevant for future fertility trends.

Consequently, this Outlook follows the approach used by the International Institute for Applied Systems Analysis (IIASA), which specifically considers how urbanization and rising education levels are linked to demographic trends.

Following the latest (2019) update from IIASA, we arrive at a global population estimate of 9.4 billion by 2050 – some 4% lower than the most recent (2017) UN median population forecast. Energy use per person varies considerably and this is reflected in our model through a weighting process in calculating aggregate energy consumption first at a regional and then global level.

The pandemic has affected both fertility levels and education, however the impacts on long-term population trends have yet to be definitely determined.

Economic growth

World GDP is expected to grow from USD 138 trn/yr in 2019 to USD 292 trn/yr in 2050. This doubling over the 31-year period is the result of a 22% increase in population and a 74% increase in average GDP per capita, with large regional differences.

The pandemic slowed economic growth to a 1.2% CAGR over the 2019-2021 period, and will leave a permanent impact on the world economy. 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 declines to 3.2%.

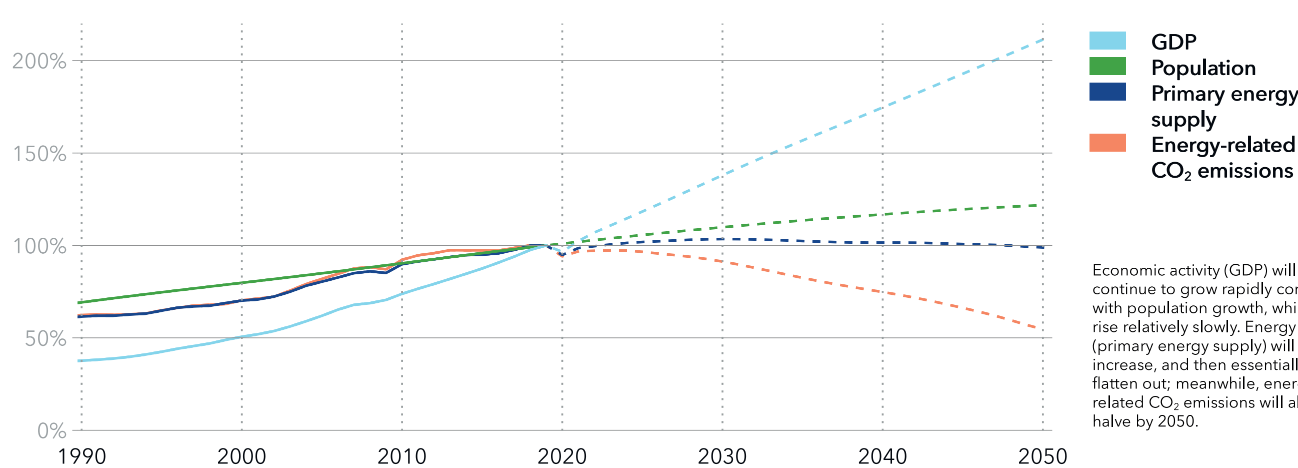
By mid-century, today's fast-growing emerging economies will experience significantly slower growth as they move into the tertiary (service) economy. The combination of slower population growth and decelerating productivity means global GDP growth rates will also slacken.

The fastest growth in GDP per capita, between 2021 and 2030, will be in Asia. The Indian Subcontinent (IND) will have the highest growth rate, at an average of 6.2%/yr, followed by South East Asia (SEA) at 4.9%/yr and Greater China (CHN) at 4.6%/yr.

FIGURE 27

The decoupling of economic growth from other key parameters

Units: **Percentages**



Economic activity (GDP) will continue to grow rapidly compared with population growth, which will rise relatively slowly. Energy use (primary energy supply) will first increase, and then essentially flatten out; meanwhile, energy-related CO_2 emissions will almost halve by 2050.

Historical data source: UN (2019), IMF (2021), World Bank (2018), Gapminder (2018), IEA WEB (2020)

Learning curves effect

The cost of a technology decreases by a fraction with every doubling of capacity. Ongoing market deployment brings greater experience, industrial efficiencies, and further R&D.

The cost of solar panels has been declining by 26% for every doubling of global cumulative capacity additions. We expect this to reduce to 17% by 2050. The cost learning rate (CLR) is 16% for wind turbines and 19% for Li-ion batteries and will continue at these rates. Apart from these core technologies, total investment costs include the costs of supporting infrastructure, installation kits, labour, legal fees, etc, which all have a lower CLR. Including these other cost components, we forecast global average of the total investment cost of relatively mature renewable technologies like solar PV and onshore wind to decline 11% for every doubling of global cumulative capacity additions until 2030. For newer technologies like solar PV + storage and floating offshore wind, the learning rates are higher. Towards 2050, CLRs will decline as non-technology costs start to constitute a higher share of the total investment cost.

The decline in investment cost only partially explains why technologies like solar and wind experience a massive uptake. Improvements in design and operation of power plants allow higher capacity factors, ensuring more energy is produced over the year per kilowatt of capacity.

Policy

Energy policy has never been under so bright a spotlight as at present – in the wake of the publication of the IPCC's alarming AR6 report, in the build-up to the delayed COP26, and amid analyses of the disappointing impacts of COVID-19 recovery spending on the energy transition.

Through our work with governments, academia, and international bodies, DNV keeps close tabs on policies that impact the energy transition at national, regional, and global levels. We constantly analyse a wide range of topics – such as climate goals, air quality, health, job creation, and energy security.

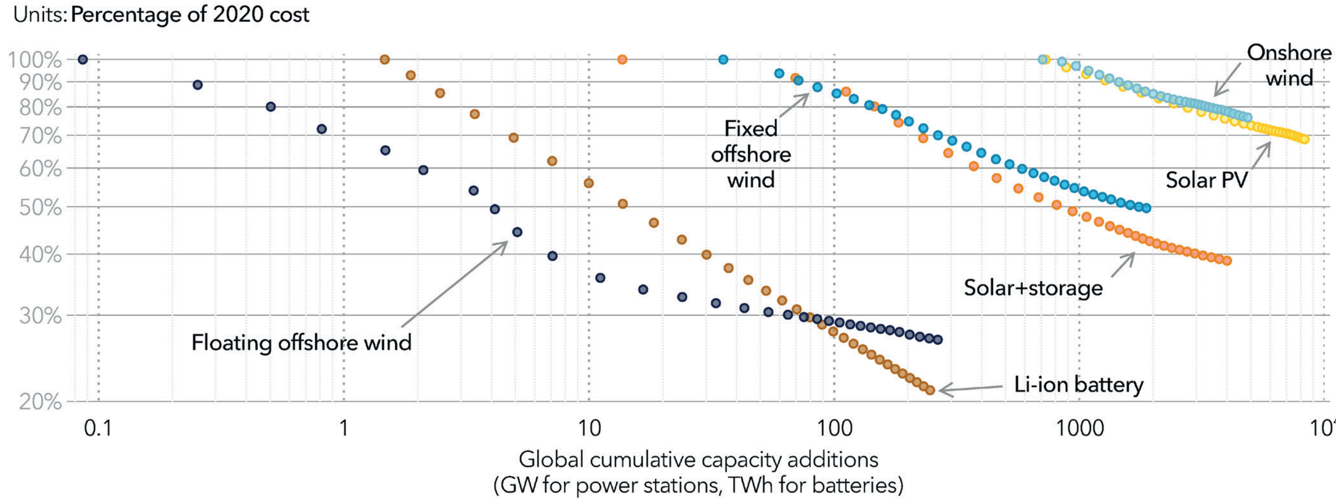
An overview of the policy factors explicitly factored into our forecast can be found on page 35.

In our model, country-level data are translated into expected policy impacts, then weighted and aggregated to produce regional figures for inclusion in our analysis. Examples include explicit regional carbon prices, support for renewable energy and EVs, and fossil fuel taxation in relation to air pollution and climate concerns. Several countries – Chile being an outstanding example – are gearing up programmes to support the acceleration of green hydrogen.

FIGURE 28

Decline in unit investment costs due to learning

Units: Percentage of 2020 cost



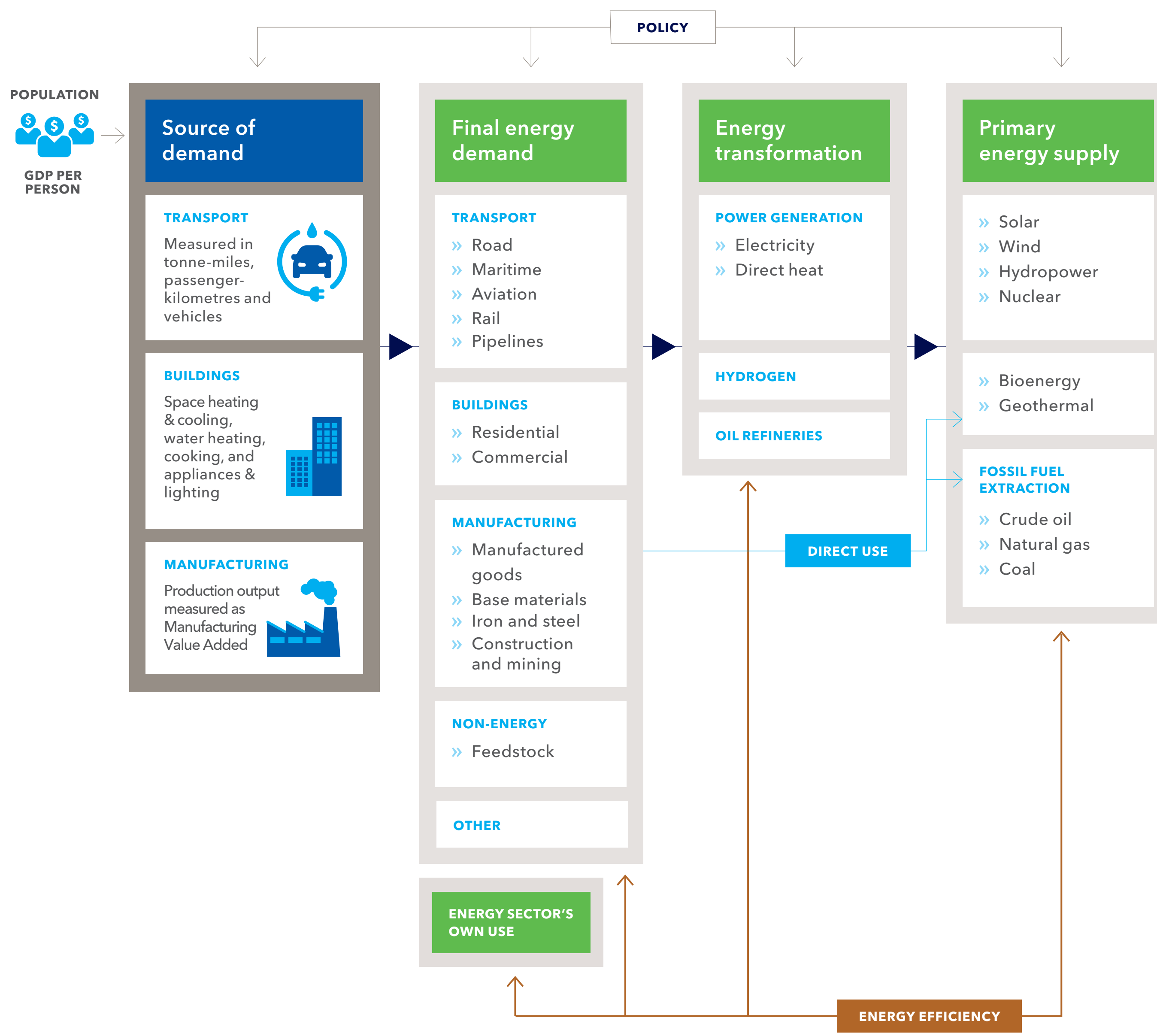
Each circle represents global weigted average cost by year from 2020-2050.

MODEL DESCRIPTION

Figure 29 below presents the ETO model framework. The arrows in the diagram show information flows, starting with population and GDP per person, while physical flows are in the opposite direction. Policy influences all aspects of the energy system. Energy-efficiency improvements in extraction, conversion and end-use are a cornerstone of the transition.

FIGURE 29

ETO model framework



Our approach

In contrast to scenario-based outlooks, we present a single 'best estimate' forecast of the energy future, with sensitivities in relation to our main conclusions.

Our model simulates the interactions over time of the consumers of energy (transport, buildings, manufacturing, and so on) and all sources of supply over time. It encompasses demand and supply of energy globally, and the use and exchange of energy between and within ten world regions. The analysis covers the period 1980-2050, with changes unfolding on a multi-year scale that in some cases is fine-tuned to reflect hourly dynamics.

Policy

Policy influences all aspects of the energy system, and Figure 30 gives a snapshot of the policy factors incorporated into our forecast. Policy considerations influence our forecast in three main areas:

a.) Supporting technology developments and activating markets that close the profitability gap for renewable-energy technologies competing with existing technologies

b.) Restricting the use of inefficient or polluting products/technologies by means of technology requirements or standards, or;

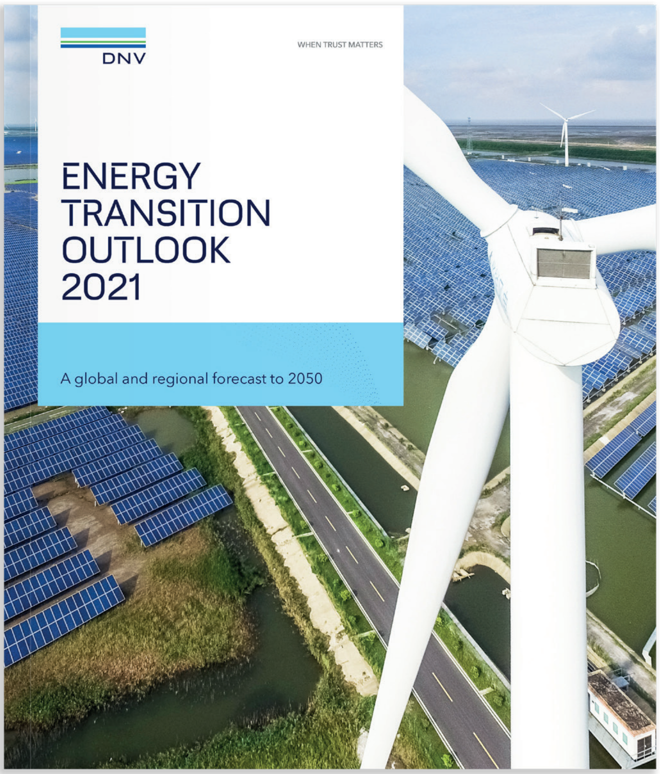
c.) Providing economic signals, for example a price incentive, to reduce carbon-intensive behaviours

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

FIGURE 30

Policy factors included in our Outlook

ENERGY TRANSITION OUTLOOK 2021 REPORTS OVERVIEW



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

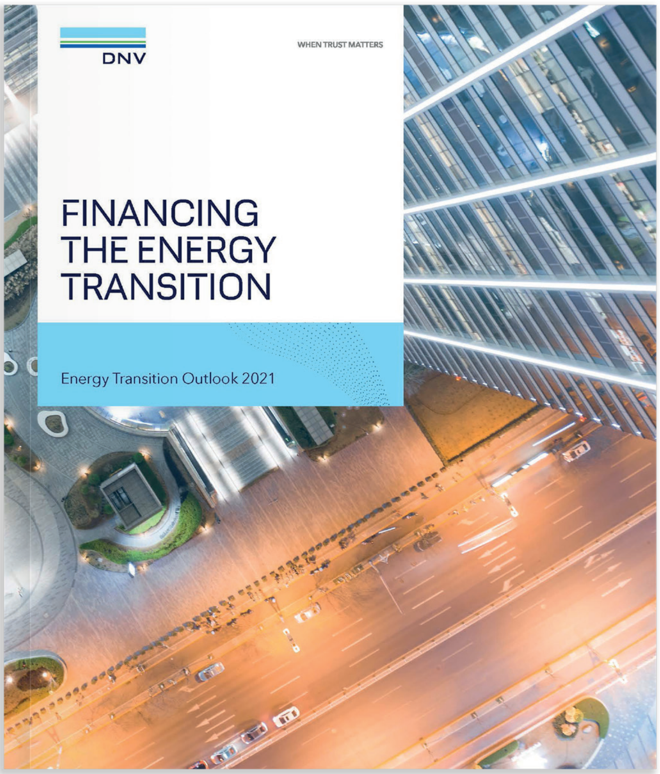
- **The global energy demand** for transport, buildings, and manufacturing
- **The changing energy supply mix**, energy efficiency, and expenditures
- **Detailed energy outlooks** for 10 world regions
- **The climate implications** of our forecast.

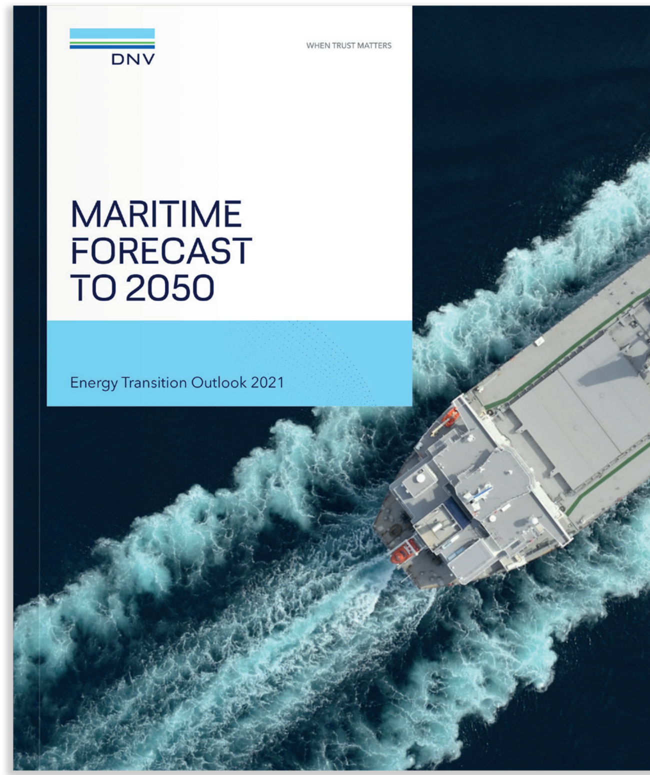
We also provide details of our model and main assumptions (i.e., population, GDP, technology costs and government policy). Our 2021 Outlook explores, inter alia, the impact of COVID-19 and the growing importance of hydrogen as an energy carrier.

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

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

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





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

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

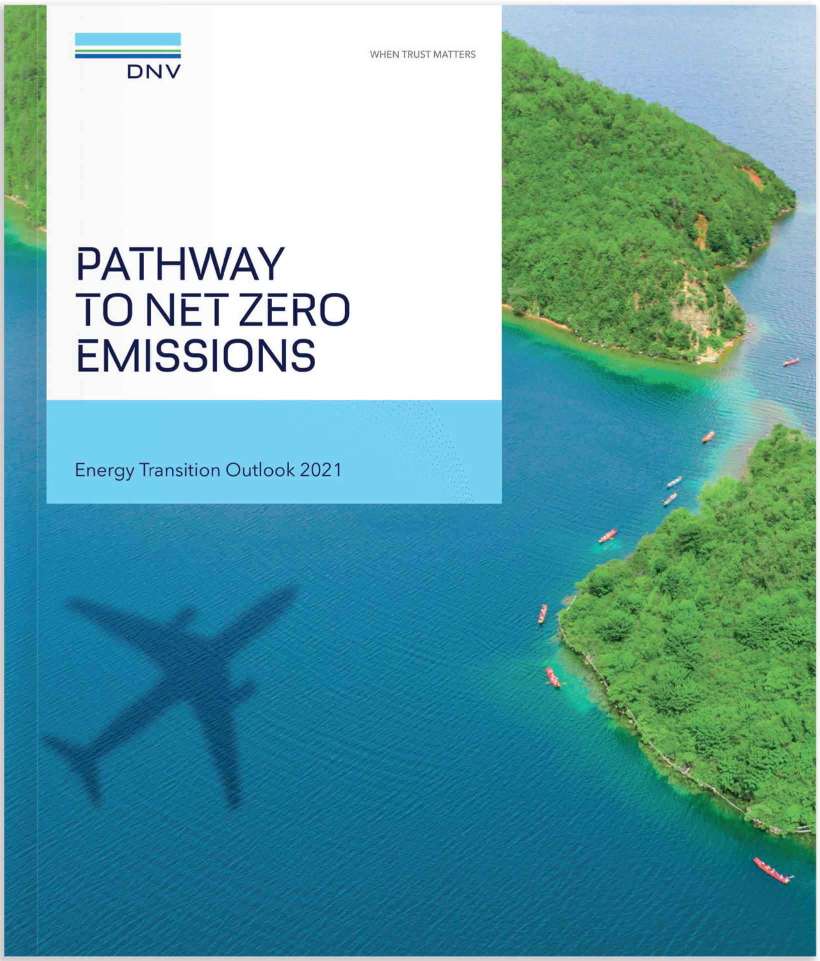
The report combines DNV's independent energy forecast to 2050 with views from a diverse set of leaders in the energy and finance sectors.

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

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

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

PATHWAY TO NET ZERO EMISSIONS



This year, ahead of COP 26, we are releasing a new companion report to our main *Energy Transition Outlook 2021*. As outlined in the Paris Agreement, and confirmed in the IPCC AR6 WG1 report released in August 2021, there is a dire need for urgent, prioritized action tackling energy-related emissions.

Our new report plots a pathway for how to close the gap between our forecast and net zero CO_2 emissions by 2050 – i.e. actions that are likely to limit global temperature increase to 1.5°C by end of this century. The report covers all energy sectors – including hard-to-abate sectors like aviation, maritime and cement – and each of the ten global regions in our *Energy Transition Outlook*. We look at which technologies will contribute to the required change and the policies needed to achieve that.

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

ETO TEAM AND CONTACT

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

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Historical data
This work is partly based on the World Energy Balances database developed by the International Energy Agency © OECD/IEA 2020, but the resulting work has been prepared by DNV and does not necessarily reflect the views of the International Energy Agency.

For energy-related charts, historical (up to and including 2018) numerical data is mainly based on IEA data from World Energy Balances © OECD/ IEA 2020, www.iea.org/statistics, License: www.iea. org/t&c; as modified by DNV.

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