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# Speed is of the essence

**CHRISTIAN RYNNING-TØNNESEN**

As this report goes to print, the global energy system faces immense pressure. Europe is in turmoil. Vladimir Putin's Russia is squeezing gas supplies. The risk of an energy deficit has caused soaring and volatile European gas prices, which have subsequently led to a dramatic rise in power prices. This has pushed many vulnerable consumers into energy poverty and reduced industrial activity. Given the global nature of fossil energy markets, the ramifications of these developments have been felt all over the world.

At the same time, climate change mitigation is more urgent than ever. The global temperature has already risen 1.1 °C above pre-industrial times, and we are feeling the effects in the form of hurricanes, wildfires and violent flooding. At the current emissions levels, the remaining emissions budget (to stay within 2 °C of warming, and as close as possible to 1.5 °C) is diminishing at a rapid pace, increasing the risk of potentially catastrophic climate damage.

For the seventh consecutive year, we are releasing Statkraft's Low Emissions Scenario – our analysis of the global energy system towards 2050.

The energy systems of the future must deliver affordable energy without compromising on security of supply or sustainability. Our future depends on it. In previous Low Emission Scenarios, climate change has been a central theme. In this year's analysis, we show that the energy crisis we currently face eventually could become a catalyst for the green energy transition. The main solution to obtaining energy security and independence is to develop clean and efficient energy at a higher pace than before.

Increased use of renewable energy, combined with technological solutions available to ensure greater flexibility, are cornerstones of the energy transition. Wind and solar power will largely outcompete fossil competitors and become the dominant electricity sources, while energy storage solutions, such as batteries, will be essential to keep balance in the more intermittent system. Hydropower and hydrogen will continue to grow in importance as emissions-free and flexible resources, while increasingly interconnected energy systems also provide needed flexibility in the renewable-dominated energy system of the future.The European Union's REPowerEU plan, which aims to remove the Union's dependence on Russian energy while achieving tough climate targets, will accelerate Europe's energy transition. In this year's Low Emissions Scenario we show that, while challenging, it is possible for Europe to become fully independent of Russian gas before 2030 – mainly through the use of mature clean technologies such as heat pumps, solar and wind, but also more energy efficiency and diversification of gas supply. Although the plan includes ambitious targets on hydrogen production, our analysis shows that reaching the EU's ambitious hydrogen targets is very challenging and will demand substantial policy development and political push to be realised.

International trade and co-operation are critical to a successful energy transition. To an increasing extent, the global energy system will move from fuel-intensive to material-intensive. Securing the supply chain for clean technologies will be increasingly important. Although there are abundant metal reserves in the world, these resources must be made available through timely investments in a sustainable manner. Currently, a large share of the critical metals supply chains for clean technologies is concentrated in just a few countries, which increases vulnerability and underlines the need for diversification.

The 2022 edition of Statkraft's Low Emissions Scenario is still an optimistic but realistic scenario, in line with continued strong market growth of renewable energy. The developing trends once considered optimistic have now entered the mainstream.

Our analysis shows that despite the pandemic and the strain that Russia's war on Ukraine puts on global supply chains, renewable energy continues to increase its competitiveness compared to fossil fuels. The energy-related CO2 emissions we now predict for 2050 are lower than in previous reports, which puts our scenario on a challenging, yet realistic 2 °C pathway.

On the road to net zero, every avoided CO2 molecule counts, and it is the carbon at the end of this journey that will be the most costly and challenging to abate. To limit the damaging effects of global warming, we must speed up the energy transition. We have no time to waste.

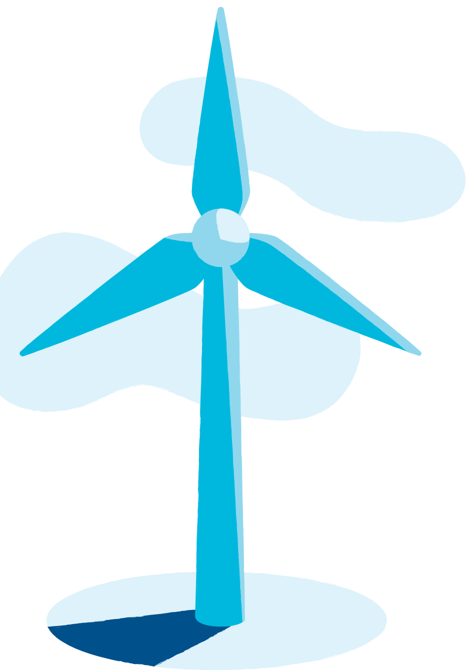
## SUMMARY OF

# Statkraft's Low Emissions Scenario 2022

The uncertainty in energy markets has increased, Western trust in the Russian regime is broken, and energy self-sufficiency is now at the top of the policy agenda.

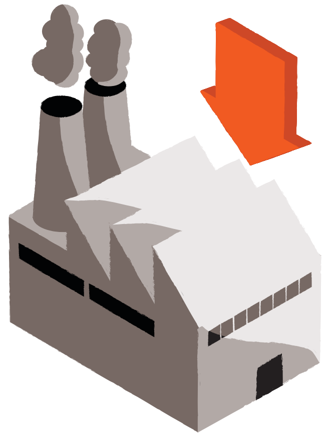
In this year's analysis, we show that developing clean and efficient energy at a higher pace than before is the main solution to ensure energy security as well as affordable energy prices. Developing renewable energy systems and enhancing energy efficiency is the long term solution, both to the current energy crisis and the climate crisis.

However, global geopolitics characterised by rivalry and conflict could make it more difficult to coordinate the global response to climate change and build trust.

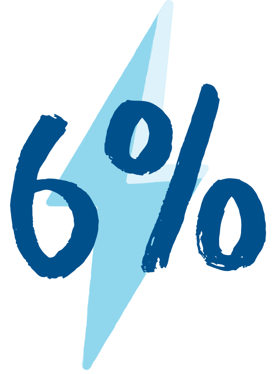


Solving the flexibility challenge in a cost-effective and environmentally friendly way is key to the development of a renewable-dominated power system. There are many different flexibility solutions that cover short time periods, and they will face high competition.

Hydropower is today the world's largest renewable energy source, and the biggest source of electricity storage with 99.9 per cent of the global capacity. Hydropower is one of few solutions able to cover the flexibility requirements over longer periods of time, such as entire days and weeks, and will play a major role in the global energy system towards 2050.



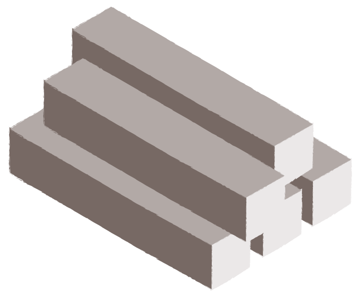
Coal and gas demand will decrease substantially – unabated coal and gas in the power mix will be reduced by 75 and 23 per cent respectively.



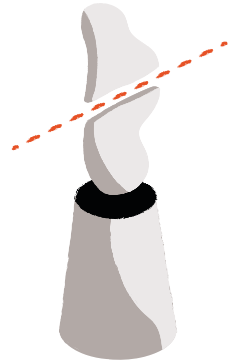
Primary energy demand will be around six per cent lower in 2050 than today.

Electrification cuts CO2 emissions and increases energy independence. Global power demand will more than double towards 2050 and solar and wind power will supply about two-thirds.

There are abundant metal resources, but supply chains for metals critical to the energy transition are concentrated in a few countries. Insufficient investment in and diversification of production capacity could postpone the energy transition.

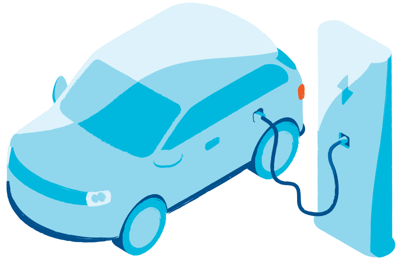


Temporary elevated metal prices have increased the costs of solar and wind, but this has not affected competitiveness compared to fossil power technologies as prices for oil, gas and coal have risen at a much higher pace since early 2020.



In the Low Emissions Scenario yearly energy-related $CO_2$ emissions are cut from 32 gigatonnes today to 12 in 2050, firmly on a path to 2 °C global warming compared to pre-industrial time. For a 1.5 °C pathway, the transition needs to happen substantially faster and go even further.

Solar power will be the global winner in the energy transition, with production increasing by a factor of 26 from today, to over 21,000 TWh in 2050. With this amount we could cover more than 80% of global power demand today.



The global passenger vehicle fleet will be all-electric in 2050, with some fuel cell hydrogen cars in niche applications – displacing more than 20 million barrels per day of oil demand by 2050.

We find that it is feasible but challenging for the EU to reach its dual targets: to become fully independent from Russian gas by 2030 while reducing emissions – increasing renewable share of electricity to two-thirds.

# Statkraft's Low Emissions Scenario:

## The Energy Transition in a conflicted world

The current energy crisis has put the global energy system to the test. Russia's invasion of Ukraine has resulted in major disruptions to the global energy systems and trade, underlining the world's dependence on volatile fossil energy markets.

While the world's eyes are on energy security and supply disruptions, global emissions continue to rise. Global $CO_2$ emissions rebounded to the highest level in history in 2021, after dipping during the COVID-19 pandemic - the biggest yearly increase on record. Global warming has already increased by 1.1 °C compared to pre-industrial levels, and we are experiencing the effects of this already.[1]

It is perhaps difficult to be optimistic at present, but Statkraft's Low Emissions Scenario shows that the world does not need to choose between solving the ongoing energy crisis or the climate crisis, and we see several positive long-term trends despite the current global situation.

There are clear synergies between a low emissions world and energy security. A transition from fossil fuels to renewable energy implies, in many regions, a transition from energy import dependency to increased energy self-sufficiency based on sustainable, reliable, and clean energy.

Statkraft's Low Emissions Scenario is a technology-optimistic but realistic scenario for the global energy transition from today to 2050. This scenario assumes that policy, markets, and technology jointly drive the energy transition towards decarbonisation. It's a scenario that does not start with a given climate target but is instead our view of what the world will achieve if the existing momentum for clean technologies and climate policies continue. The scenario also takes into consideration the current energy crisis and the global geopolitical situation.

The power sector is in the midst of a massive transformation with a rapid shift towards renewable technologies. New capacity additions are dominated by solar and wind power which have shown record growth for several years in a row. Solar and wind outcompete other technologies on cost and in terms of benefits to the climate, while making countries and regions less dependent on fossil fuels imports.

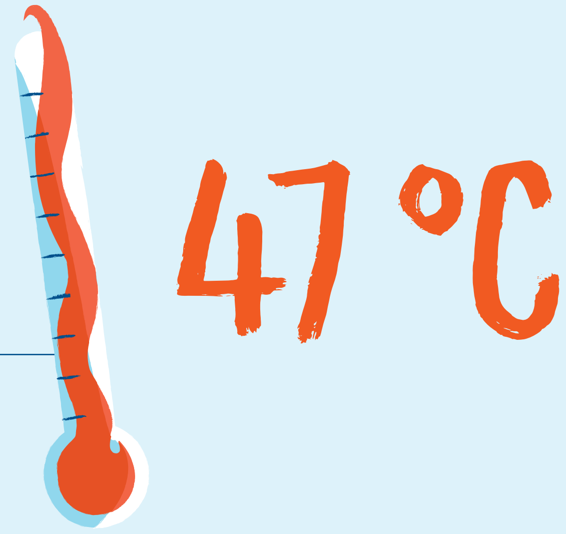
Tougher climate targets add to the pressure on industry, transport, and buildings to cut emissions. To achieve our global climate and sustainability goals, it is imperative to use energy more efficiently. Using renewable electricity is in most cases far more efficient than burning fossil fuels, meaning that less energy is needed to produce the same heat, light or work. With a more renewable power sector, direct use of electricity will be a cost-effective climate measure in end-use sectors, saving energy and reducing both local pollution and global greenhouse emissions in the process.

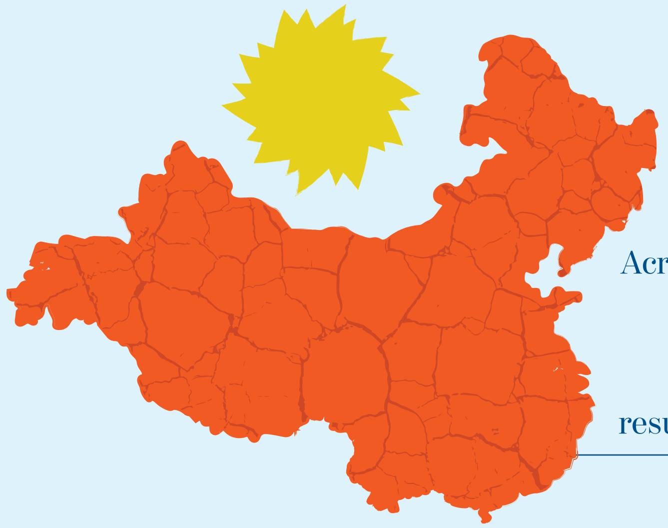
In sectors where direct use of electricity is not feasible, using renewable energy indirectly through green emission-free hydrogen becomes increasingly attractive. This indirect and direct use of renewable energy links the different sectors together through sector coupling, providing much needed flexibility to the energy system. Sector coupling can reduce the need for flexible fossil power production and support investment in intermittent renewable technologies such as wind and solar power.

Hydropower also plays and will continue to play an important role in providing low emission flexibility and reliability to a variable renewable energy system. While there is enormous potential for hydropower globally, it is only viable under certain conditions and in certain areas of the world. More weather dependent power production calls for better integrated power systems across regions, in order to benefit from the differences in each power system and increase access to flexible solutions.

Although there are several positive trends, efforts must accelerate to meet climate ambitions, and we already have the technologies that enable us to do so. According to the IPCC, we have only 400 billion tonnes (400 Gt) carbon remaining in the carbon budget to limit warming to 1.5 °C - with 67 per cent likelihood.[2] Given the average yearly emissions of 39.4 Gt $CO_2$ over the last decade,[3] the world's carbon budget will be spent within the next 10 years if the current level of emissions is maintained. Hence, strong and immediate action is required to keep us within the climate targets.

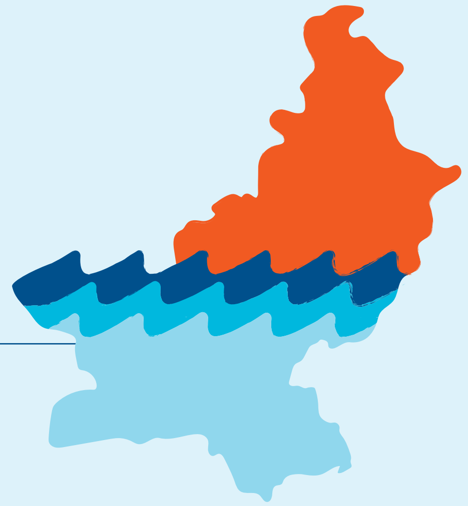
This year, the worst heat waves on record in Europe have caused wild-fires, the worst drought in over 500 years and over **50,000 excess deaths,** with temperatures surpassing **40 °C** in the UK, France, Germany, Italy, Portugal, Slovenia and Spain. The highest temperature was recored in Pinhão in Portugal **(47 °C).**[4]





During the summer, the worst heat wave in Chinese history, perhaps the most severe heat wave recorded anywhere, has swept through the country. Across several regions record high temperatures have been recorded, bringing intense drought, killing crops and causing wild fires - sucking dry the Yangtse river and **reducing hydropower generation by 50 percent**, resulting in a servere energy crisis in the regions affected. [5]

Since June 2022, extreme monsoon rains and melting glaciers following a severe heat wave, have resulted in flash floods, putting one-third of Pakistan under water, affecting **33 million people.**[6]



To mitigate the risks associated with global warming, we need to electrify industry, transport and buildings while we at the same time accelerate investments in clean energy production. We need to act now.

Industry, ships, power plants and infrastructure have a lifetime expectancy of 30 years or more, potentially locking in emissions far into the future. It is therefore vital that policy makers provide a clear signal to markets to shift away from fossil fuels as soon as possible. Carbon pricing is an efficient and transparent way for policy makers to steer investments from fossil fuels to renewables. To ensure sufficient pace, carbon pricing will have to be supplemented with other policies that spur on technological development and more investments in clean technologies.

The scale and speed needed to limit global warming is a monumental challenge. In the nearer term, numerous mature clean technologies are readily available to be scaled quickly. Solar and wind power generation, heat pumps, electric vehicles, more efficient appliances, better insulation, reusing heat, as well as bioenergy and renewable hydrogen can all contribute to lower emissions already before 2030, reducing the demand for expensive fossil fuels. In the longer run, the final 10-20 per cent of emission reductions needed to reach net zero in the "hard to abate"[i] parts of industry and transport will be challenging. It is therefore important to develop promising, less mature technologies in parallel, such as clean hydrogen, carbon capture and storage (CCS) and carbon removal technologies.

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[i] The «hard-to-abate" sectors are the sectors where emission cuts are more costly, often based on technologies that are not yet mature. These sectors are for example heavy duty transport, shipping, aviation, iron and steel, cement, chemicals etc.

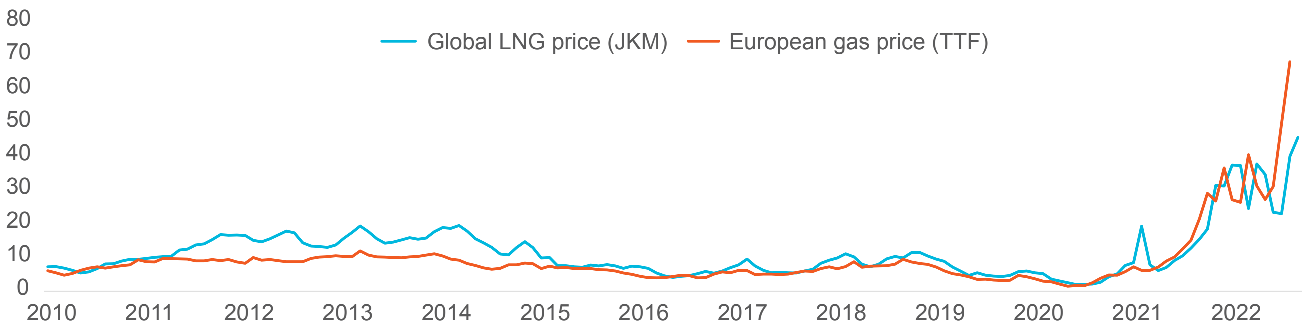
PART 1

# ENERGY SECURITY IS A POWERFUL DRIVER FOR A LOW EMISSIONS SCENARIO

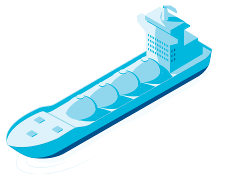
The current energy crisis is putting the global energy system to a test.
This chapter examines how energy security has moved up on the political agenda with surging fossil fuel prices, and how renewable energy and energy efficiency can shift energy trade flows and power balances. Solar PV and wind power technology costs continue to outcompete fossil fuel technologies in more and more regions. Shifting to a renewable energy system will reduce the dependence on a small number of big commodities exporters. At the same time, vulnerability in supply chains is changing when moving to a more material-intensive system.

# The current energy crisis

1 Historical monthly gas prices for global LNG and Europe, Jan 2010 – Sept 2022 (USD/mmbtu)

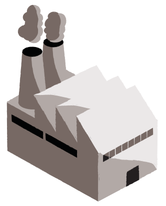


**Fossil gas and electricity prices have reached record levels in 2021 in Europe and hit all-time highs following the Russian invasion of Ukraine. The invasion disrupted global energy markets and exacerbated the high energy prices. There is high uncertainty in the energy markets and a risk of further gas supply disruptions. The extreme gas prices have knock-on effects for the electricity prices, inflation levels, on industry production costs and on cost of living. The increased costs have pushed millions of people into energy poverty and is impacting the overall macroeconomic stability in Europe and worldwide.**



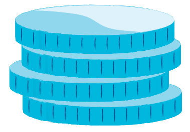
Already in the second half of 2021, Russia started to decrease the flow of pipeline fossil gas to Europe. Russian gas covered around 40 per cent of European gas demand. This has dropped to around 9 per cent at time of writing as Russia exploited its market position, squeezing the European market. Low Russian gas flows resulted in higher European LNG demand, diverting cargos to Europe and spreading the energy crisis globally.

Extreme heat waves and drought caused low hydropower output in Europe and China. In addition, there is historic low French nuclear output due to technical issues and high river temperatures which resulted in insufficient cooling.



One short-term solution for balancing the electricity system is to run more coal power. Germany and others have allowed coal and lignite reserves to return to market. Higher coal demand and partial ban on Russian coal have resulted in higher coal prices. In Europe, transport costs have also increased due to low water levels in many rivers.

Swift and unified policy responses in the EU to become independent of Russian gas before 2030. Agreement on mandatory gas storage levels, gas demand reductions and accelerating build out of renewables, heat pumps and hydrogen. Energy market design interventions to reduce stress in the European electricity system are on the table.



Negative spill-overs from the war in Ukraine, but also other shocks such as new COVID-19 outbreaks and lockdowns in China, have hit the world economy. We see higher-than-expected inflation worldwide and tighter financial conditions in many countries.

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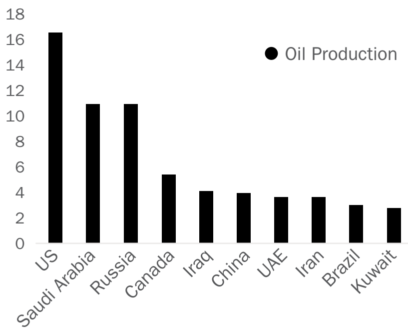
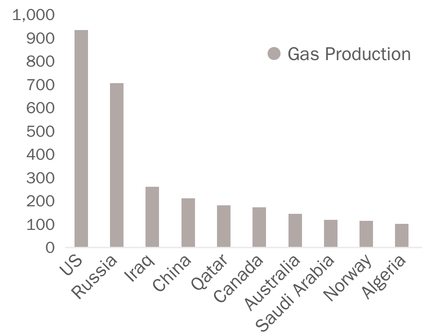
# Dependence on fossil fuel imports today

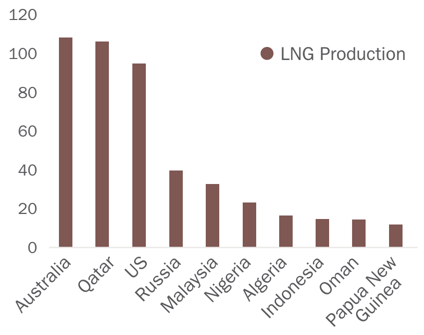
2 Top ten oil producers by production (2021) (million barrels per day)



3 Top ten gas producers by production (2021) (Billion standard cubic meters - BCM)



4 Top ten LNG producers by production (2021) (BCM)



**Around 80 per cent of the world's primary energy demand is covered by oil, gas, or coal. The power sector is dominated by coal and gas, accounting for almost 60 per cent of global power generation. Around 70 per cent of oil demand, 25 per cent of fossil gas demand and 20 per cent of coal is traded, either globally or inter-regionally.[7] In sum, this makes the world very dependent on fossil fuels, and many countries exposed to the volatile prices of the global commodity markets.**

The biggest oil producers in the world are the US, Saudi Arabia, and Russia (Figure 2), and they make up more than 40 per cent of the global supply of oil. If you include the rest of OPEC, they make up almost 60 per cent. In total National Oil Companies (NOCs) account for more than 60 per cent of global oil reserves, giving market power to just a few countries. The biggest gas producers include the US and Russia (Figure 3) – with the biggest gas resources located in Iran.[8]

Both oil and gas production are finite, and as reservoirs deplete over time there is a natural decline in both oil and gas production. For oil, a commonly assumed global average decline rate is three per cent per year. This means that investments in new and existing production are required to provide stable supply. The world's largest oil and gas fields averaged 5.5 years from discovery to first production. This makes timely investment in fossil fuels important in a fossil intensive system, making it prone to under- and overinvestment cycles and volatile prices with increased uncertainty regarding future demand.

Oil is a globally traded commodity, meaning it is easier to diversify supply sources. For gas however, only a small part of the supply is traded on the global market. Fossil gas is not very energy dense in volume, making it difficult to transport in ships and tanks in gas form. Around 60 per cent of the world's fossil gas inter-regional trade is through pipelines, which makes countries and regions heavily dependent on big fossil gas exporters in close proximity. A good example is Europe, which accounts for more than 50 per cent of global fossil gas pipeline imports, mostly from Russia.[9]

Liquified Natural Gas (LNG) makes it possible to transport fossil gas by ship. However, this is more expensive, as LNG requires big facilities both to liquify the gas near the production site, and regasify it near the consumption centres. Many regions and countries are building regasification facilities to diversify their supply, but new liquefaction capacity typically takes two to five years before coming online.
Also, there are only a handful of countries globally that export LNG, with the four biggest, Qatar, Australia, the US, and Russia, accounting for around 65 per cent of the market (Figure 4). US, Qatar, and Russia are among the most ambitious in increasing capacity going forward.[10] However, with the time lag before new LNG projects come online and projected increase in LNG demand from Europe to replace Russian imports, the market expects high and volatile gas prices in the coming few years compared to the prices over the last two decades.

Compared to gas, an even smaller share of the coal market is traded globally - less than 20 per cent. This market is less liquid and transparent compared to the gas and oil markets. There are large differences when it comes to the physical coal qualities and prices, but often the European thermal coal price is used as reference.[11] The seaborne thermal coal market is heavily influenced by Chinese government policies related to imports, domestic supply, and price control. The Pacific market and Asia are driving demand and dominating the traded coal market, while the Atlantic market share is less than 15 per cent today and declining. Currently, strong global demand and the European ban on Russian coal have resulted in a tight global market for high quality coal and higher prices.[12]

Energy security is an important topic on the Chinese policy agenda. Currently, 75 per cent of Chinese oil demand and 40 per cent of gas demand are imported. China has huge domestic coal resources, but their reliance on coal as the primary source of energy has put a huge strain on the rail system. Coal is also contributing to urban air pollution, acid rain, as well as climate change. Increasing energy security with energy efficiency and renewables, reducing the share of fossil fuels in energy consumption, while decreasing air pollution are cornerstones of China's five-year plan from 2021.[13]

More efficient use of energy, more renewable energy, and more direct use of electricity to replace oil, coal and gas, will reduce dependence on fossil fuel imports.

# What is energy security?

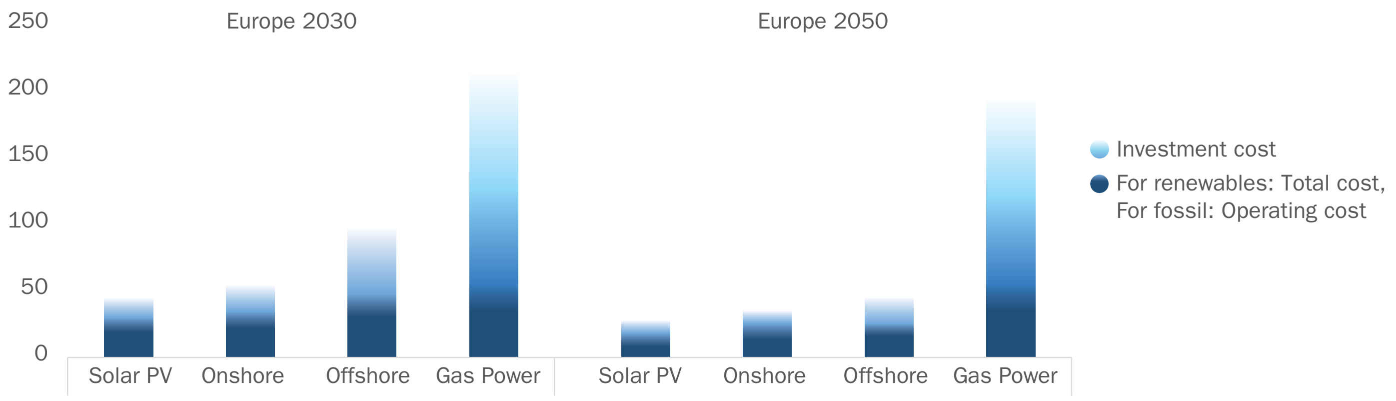
There are many different definitions for energy security, and the term can have different interpretations according to various stakeholders, regions, and timescales. The IEA defines energy security as the uninterrupted availability of energy sources at an affordable price.[14] This definition can refer to long-term energy security through timely investments to supply energy in line with economic developments and environmental needs, as well as short-term energy security, in order to deal with sudden changes in the supply-demand balance.

Energy security often entails limiting vulnerabilities in energy systems by diversifying supply, reducing import dependence, improving infrastructure to increase the resilience of a system, securing system adequacy, ensuring robust supply chains, and strengthening emergency preparedness.

Conflict and increased emphasis on energy independence and security of supply could be a catalyst for the green transition. Reliance on imported energy supplies expose countries and regions to significant economic and geopolitical risks. More efficient use of energy, more renewable energy, and more direct use of electricity to replace oil, coal and gas would reduce dependence on fossil fuel imports and the impact of volatile commodity prices – increasing energy security and economic resilience.[15] If the current extreme energy prices spur more renewable energy investments, the current crisis may eventually accelerate the green transition.

On the other hand, a shift from fossil fuels to renewables is not a cure-all. Going from being dependent on the major fossil fuel exporters to increased reliance on countries controlling the clean technology value chain gives rise to other challenges – such as changing the energy trade flows and shifting the power balance.

5 Levelised Cost of Energy (LCOE) for different power producing technologies in Europe in 2030 and 2050 (EUR/MWh)



# From a fuel-intensive system to a material-intensive system

One big advantage of a renewable energy system is that countries and regions take more control over their own energy supply and reduce dependence on a small number of big commodities exporters and high and volatile fossil fuel prices. A renewable energy system is part of the solution as it will make countries and regions more energy self-sufficient, giving their populations affordable, reliable and clean energy while cutting emissions. Energy systems based on variable renewable generation are vulnerable to weather-driven fluctuations in electricity supply, and flexibility solutions need to scale up to handle these fluctuations.

However, a transition to a renewable energy system does not imply that countries or regions will become energy islands. The transition will entail a switch from a fuel-intensive system to a material-intensive system, which will likely result in a massive reshuffling of energy trade patterns. The energy transition could alter the geopolitical landscape, shifting power from countries with high oil, gas and coal resources to countries leading the clean technology race and controlling critical materials. Countries endowed with metals and other natural resources that are critical to the energy transition may have a competitive advantage if exploited properly. The resources are there but must be made available through timely investment. Underinvestment in critical raw materials for wind, solar and battery technology could postpone, or, in the worst case, derail the energy transition.

## Solar and wind power remain competitive despite recent cost increase

Renewable capacity additions are posting record growth despite pandemic related supply chain challenges, construction delays and elevated prices for raw materials. In 2021 annual renewable capacity additions increased to almost 300 GW, a six per cent increase compared to 2020 according to the IEA. China is driving this growth, accounting for 46 per cent of worldwide renewable capacity additions, followed by the EU and the United States.[16] For China, there are clear synergies on export policy, as well as on an economic, strategic and national security level, for moving to renewable power. Electrification with clean energy reduces the need for coal without increasing dependence on imported oil and gas.

Wind power costs have fallen by more than 50 per cent since 2010 and cost reductions exceed 80 per cent for solar PV, which has led clean energy technologies to dominate energy investments.[17] Climate policies have helped drive down the cost of renewable energy and cheaper renewable energy has reduced the cost of achieving climate targets. This has created a powerful dynamic around the world, in which fossil energy is being outcompeted by renewable energy. Costs are expected to continue to decline and installing new renewable power production is becoming cheaper than the operating costs of existing coal and gas power plants in more and more places around the world (Figure 5).

The competitiveness of renewables compared to fossil power generation has been reinforced by the high fossil fuel prices in most markets over the last year, although we have also seen an increase in renewable technology costs.

Costs for many raw materials and freight have increased substantially since early 2021 (Figure 6), resulting in higher costs for manufacturing and transporting wind turbines and solar PV modules. Rising costs in critical raw materials have resulted in increased solar module costs by more than 25 per cent and onshore and offshore wind turbines by around 10 per cent and 12 per cent, respectively.

↓ In 2021 annual renewable capacity additions increased to almost 300 GW, a six per cent increase compared to 2020 according to the IEA. China is driving this growth, accounting for 46 per cent of worldwide renewable capacity additions.

However, these higher costs have not adversely affected the competitiveness of solar and wind compared to fossil power technologies, as prices for oil, gas and coal have risen at a much higher pace since the last quarter of 2021.

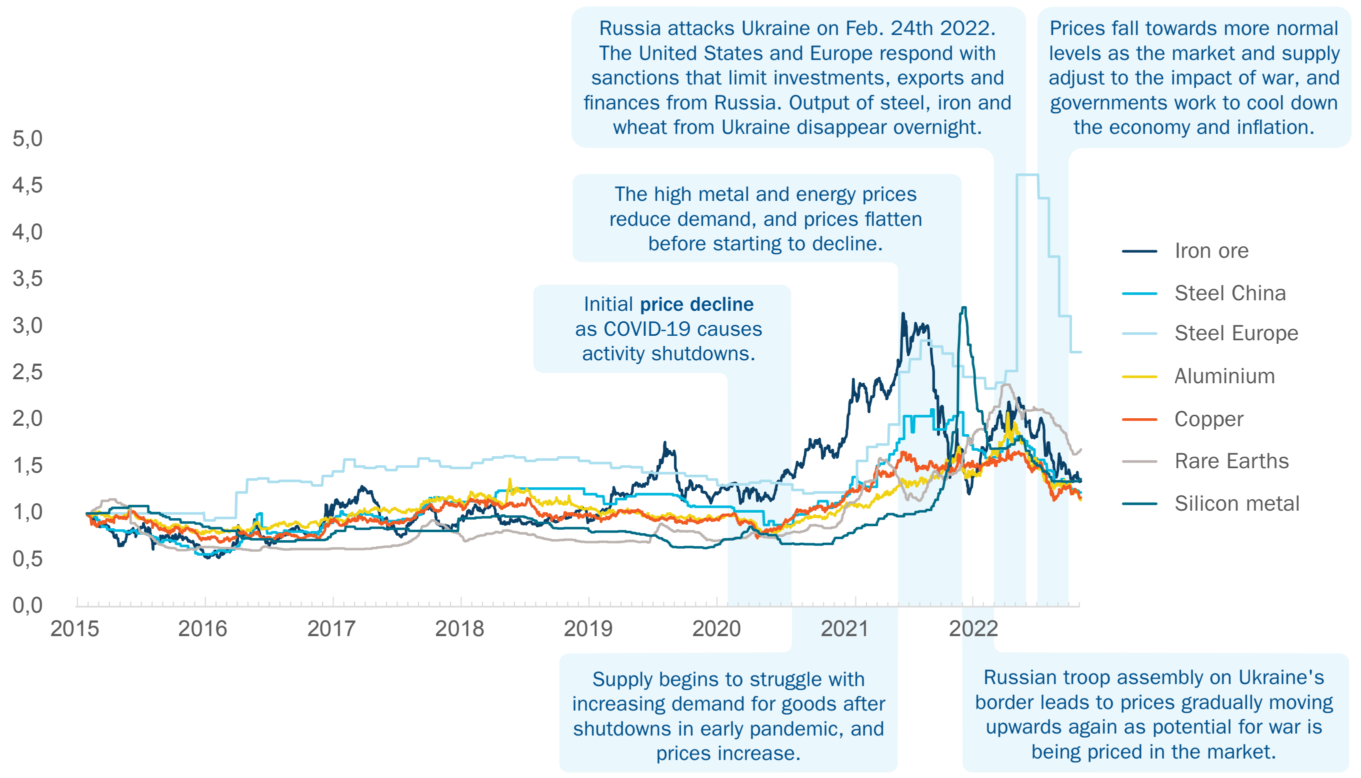
China has taken a leading role in the industrial clean technology race globally by investing large sums in renewable technology value chains, both domestically and abroad. Much of the production and refining of critical raw materials for renewable technologies is concentrated in China, as they have built-up supply chains for many renewable technologies.

Currently 90 per cent of battery production capacity, more than 80 per cent of the global solar panel supply chain and more than 50 per cent of the processing capacity for lithium, cobalt and graphite are located in China. In addition, 50 per cent of global wind turbine production is found in China.[18] This gives China a strategic advantage as the world becomes increasingly dependent on cheap Chinese clean technology to reach their climate targets. Both the US and EU have responded to this with policy, tariffs, and taxonomy initiatives to put the spotlight on sustainable supply chain development and to offer greater support to local and regional manufacturers. To reduce vulnerability in supply chains for clean technologies, it will be key to build processing capacity, increase recycling and diversify sourcing of metals and minerals. A stronger emphasis on local and regional supply chains could reduce the vulnerability but it may also increase the cost of renewable energy and the energy transition, which could slow down the spread of innovation across borders.

## DEEP DIVE

# Metals in renewable energy

6 Metal prices, normalized to 2015[20] (Iron ore, steel, aluminium, copper, rare earths, and silicon metal)



Russia attacks Ukraine on Feb. 24th 2022. The United States and Europe respond with sanctions that limit investments, exports and finances from Russia. Output of steel, iron and wheat from Ukraine disappear overnight.

Prices fall towards more normal levels as the market and supply adjust to the impact of war, and governments work to cool down the economy and inflation.

The high metal and energy prices reduce demand, and prices flatten before starting to decline.

Initial **price decline** as COVID-19 causes activity shutdowns.

Supply begins to struggle with increasing demand for goods after shutdowns in early pandemic, and prices increase.

Russian troop assembly on Ukraine's border leads to prices gradually moving upwards again as potential for war is being priced in the market.

Demand for metals is expected to increase sharply due to the energy transition. This calls for a large and more sustainable build-out of new mining, processing, refining, and recycling capacity. The deep dive examines the current disruptions in metal supply, the impact on solar PV, wind and battery costs, and also the longer-term perspective of demand and supply in the context of the energy transition.

### Why metals are important

Metals are increasingly important for energy markets as the world transitions towards more renewable energy. Metals are critical for the deployment of wind power, solar PV, batteries, electric vehicles, and grid transmission infrastructure. Failing to secure a sufficient and sustainable supply of metals could slow down the growth of these technologies, thereby limiting the world's ability to accelerate the clean technology build-out. Metals, like all commodities, experience volatility and price cycles driven by supply and demand imbalances. The current disruptions in metal supply have been visible since early 2020, when the COVID-19 pandemic hit the world, constraining supply chains globally. The elevated prices were sustained by further supply disruptions from the Russian war against Ukraine (Figure 6).

After summer, prices have moved down, and going forward prices are expected to come down to more normal levels. High margins are already driving new supply build-out, and key metals have ample known reserves. Still, the demand for certain metals is expected to increase sharply due to the energy transition, which would call for a large and more sustainable build-out of new mining, processing, and refining capacity. Recycling will also be important long-term. The mining, processing and refining capacity for key metals are concentrated in a few countries often associated with human rights and sustainability issues, adding risk to the supply chains. For example, China controls more than 80 per cent of the solar PV value chain (polysilicon, ingots, wafers, cells, and modules), a share that is expected to grow to nearly 95 per cent in the coming years based on manufacturing capacity under construction.[19] EU and the US have therefore recently laid out plans to secure access to critical metals through the Critical Raw Material Act (EU), the Inflation Reduction Act, and the Defensive Production Act (the US) in order to diversify supply and secure domestic production capacity.

← Steel is used for wind turbine towers, the turbine nacelle, and foundations, as well as for the mounting rack holding the solar modules.

## Main metals used in wind, solar and battery development

### STEEL

Steel is used for wind turbine towers, the turbine nacelle, and foundations, as well as for the mounting rack holding the solar modules, and for transmission grid towers. Less than five per cent of global steel demand in 2040 is expected to come from energy transition usage, as the majority will be used in the construction and the transport sectors.[22]

Steel supply has more than doubled over the last 20 years without any lasting effects on price. Most of the production is concentrated in China (Figure 7). Reserves of iron ore cover around 100 years usage at today's production levels. The biggest structural price risk, in addition to possible short-term imbalances, are the energy and emission costs from the carbon intensive production. As of now clean hydrogen, as well as recycling, looks to be the most viable option for decarbonising steel, with added costs for the former. Even so, this cost is expected to be well below current elevated price levels.

### ALUMINIUM AND COPPER

Copper and aluminium are widely used in the energy transition, mostly for transmission and distribution grids. In addition, aluminium is used for solar module frames, while copper is used as an electrical conductor in wind turbine generators, in cables connecting wind turbines and solar modules to the grid and in batteries. The energy transition build-out could account for one fourth of global aluminium demand and near half of global copper demand by 2040.[23]

Nearly one-third of aluminium costs are energy related. The high electricity prices led to temporary production shutdowns in China and Europe, causing an imbalance in supply and demand in 2022. This became even more evident when capacity from Ukraine shut down, adding to the short-term price risk. Copper needs to be extracted from mines and purified, and costs have increased as copper content in the ores has been falling over the last years. This has been somewhat offset by improved production methods. Investors are slightly reluctant to invest in new mining capacities due to the lower ore purity and the heavy dependency on Chile and Peru, who hold 36 per cent of global copper supply (Figure 7).

### SILICON

Silicon is used in solar modules to convert solar radiation to electricity. Even though silicon is the primary metal in solar cells, the huge growth in solar is expected to account for around one tenth of global silicon demand by 2040 (slightly more if battery chemistries containing silicon are included).[24] Silicon is primarily used for aluminium production, pharmaceuticals, and semiconductors - the latter being highly important for other parts of the energy transition as well.

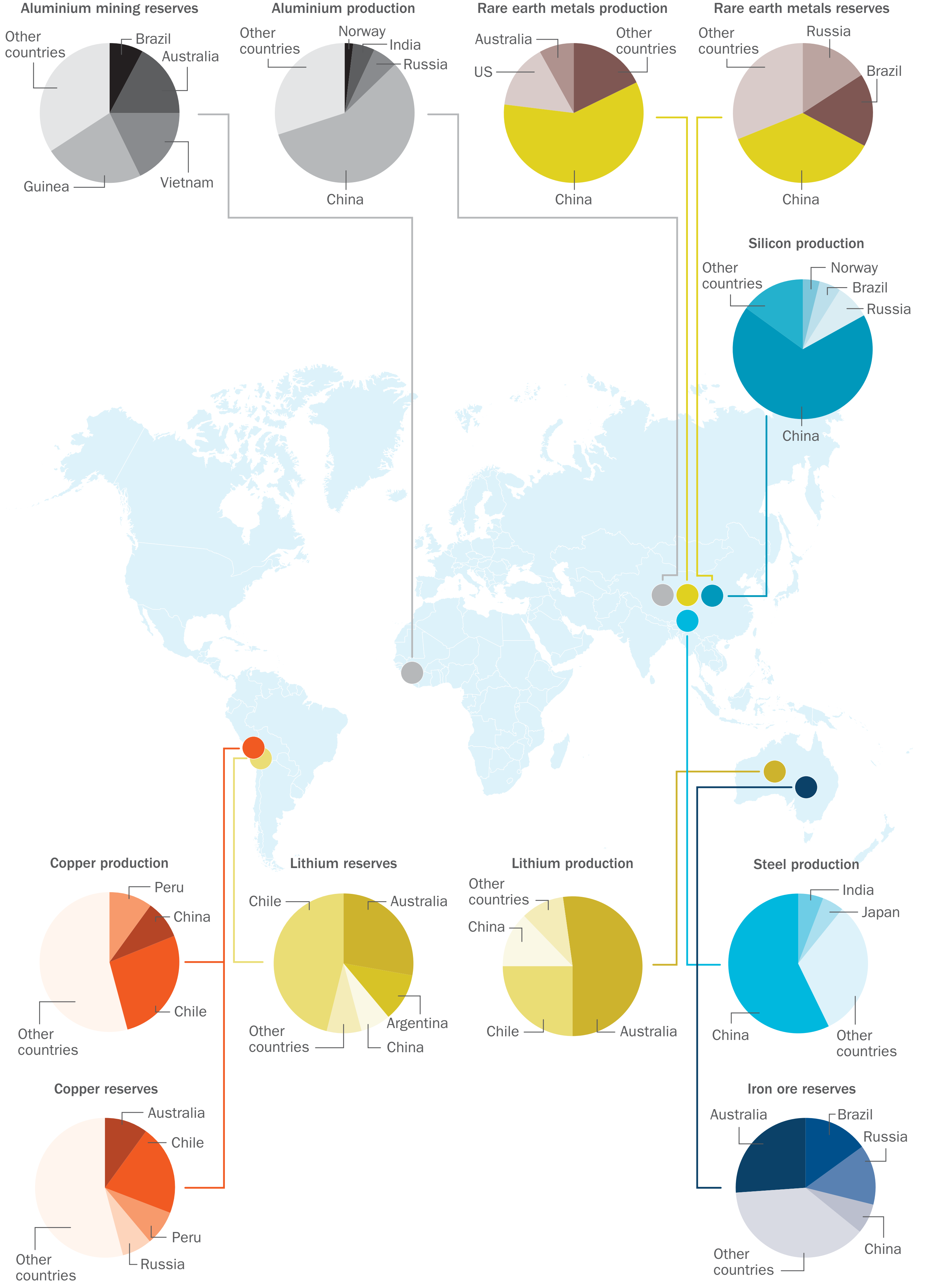
Due to high demand growth, solar grade silicon is currently undersupplied, but this is expected to improve already in early 2023, when 70 per cent of new capacity will come online. The main challenges are related to high energy consumption and the use of fossil fuels, but this can be offset by using clean electricity.

China controls almost all global solar grade silicon production which has shown to create some delivery risks during the pandemic (Figure 7).

### RARE EARTHS

Rare Earth elements consist of 17 metals, of which four are used for electric generators and motors. These are neodymium, praseodymium, dysprosium, and terbium. Neodymium magnets are the strongest permanent magnets available and are used in wind turbine generators and EV motors. Praseodymium contributes to the

**7** Production and reserves for steel, lithium, rare earth metals, copper, silicon, and aluminium per country[21]



magnetic strength, while dysprosium and terbium improve resistance to demagnetisation, particularly at high temperatures.[25]

The rare earth metals are relatively abundant in the Earth's crust, but minable concentrations are less common than for most other metals. They are often bundled together which means multiple rare earth metals are mined simultaneously. This leads to some metals being lower priced due to oversupply, while other rare earth metals can be very expensive.

There is a substantial supply risk in connection with rare earth metals as most of the mining and refining is in China and Russia (Figure 7).[26]
There are also environmental concerns, as many rare earth ores contain radioactive elements, and extraction and processing could be harmful to the soil, water, and human health.[27] However, there is ongoing research to produce magnets without expensive terbium and dysprosium, and there are also alternative generator types available that eliminate the need for magnets all together.

The energy transition is driving demand growth for many of these metals, and up towards half of global demand for neodymium could come from electric cars. Wind turbines could account for more than half of terbium demand in 2040.[28]

**LITHIUM, COBALT AND NICKEL**
Lithium, cobalt, and nickel are critical raw materials for lithium-ion batteries (nickel is also used in onshore and offshore wind turbines). The batteries are used for electric vehicles which will be the main driver for demand growth for these materials going forward. Lithium, cobalt sulphate, and nickel sulphate are used in the cathode of the battery. Lithium can be used for most batteries, but the two latter materials are more dependent on specific types of lithium-ion technologies.

Lithium experienced a price surge in 2021, but with new capacity coming online in the coming years, supply is not expected to be a constraint going forward. The biggest miners for lithium are in Australia, Chile, and China, with new capacity also coming from Argentina, Canada, Mali, Mexico, and Zimbabwe, creating a more diversified supply mix (Figure 7).

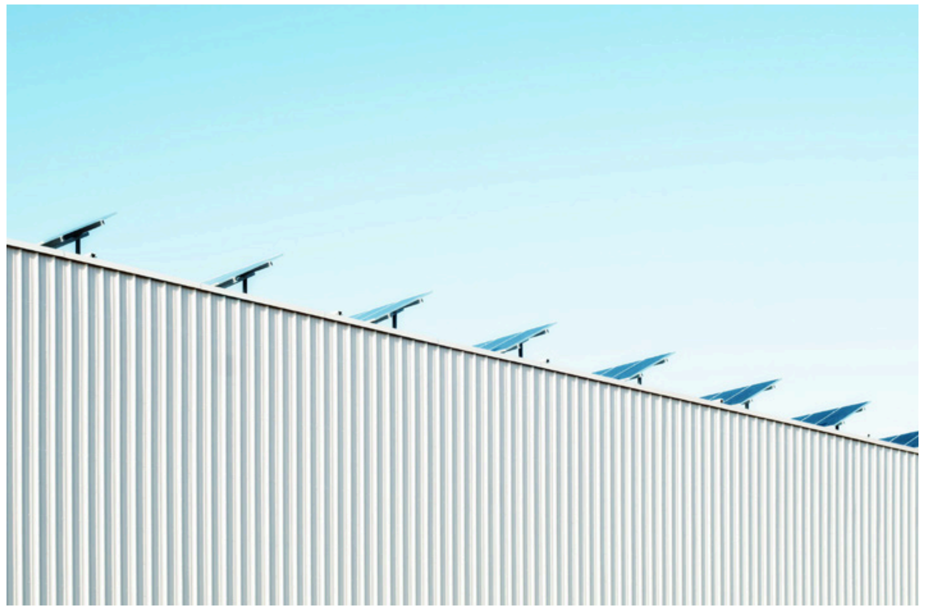
Automakers and battery manufacturers have identified cobalt as a key risk to their supply chains. The primary reasons are the historic price spikes and the fact that 70 per cent of production is concentrated in the Democratic Republic of Congo, where there are widespread problems related to health and safety standards, child labour and corruption (Figure 7).[29]
As a consequence, companies are reducing the cobalt content in their battery chemistries, shifting to more nickel cathodes and higher uptake of Lithium-iron-phosphate (LFP) batteries, thereby reducing global demand growth expectations for cobalt going forward.

The shift to nickel cathodes has led to a tighter nickel market which is expected to stay tight as nickel mines typical have lead times of two to five years, making timely investment in new capacity important. Nickel refining capacity is faster to build, so it is expected that the market will stay balanced, but it may potentially tighten towards 2030. Indonesia is the centre of nickel production growth and new supply is expected to reduce the risk linked to Russia's 20 per cent market share for battery grade nickel. There are, however, a wide range of sustainability issues when extracting and processing nickel that must be addressed. Sulphide dioxide emissions, arsenic, chlorine, and fluorine emissions are linked to extraction and refining from sulphide orebodies. Laterite mines are often spread across large tropical areas, affecting tropical rainforests, and the tailings from the leaching processes can contain heavy metals.[30]

## Metals price effects on wind, solar and battery developments

Metals play an important role in development of wind and solar generation. The elevated metal prices in 2021 and 2022 have increased the costs of onshore wind turbines by around one tenth compared to pre-pandemic levels, and offshore

**↑ There is a substantial supply risk in connection with rare earth metals as most of the mining and refining is in China and Russia**



← The elevated metal prices in recent months have increased solar module costs by more than one-third since early 2020.

wind turbines even more as there are more rare earth metals in the generator. Cost increases in non-metal materials such as resins and glass fibre for the turbine blades, freight, and labour have resulted in a 20 to 25 per cent increase in turbine prices since early 2020.

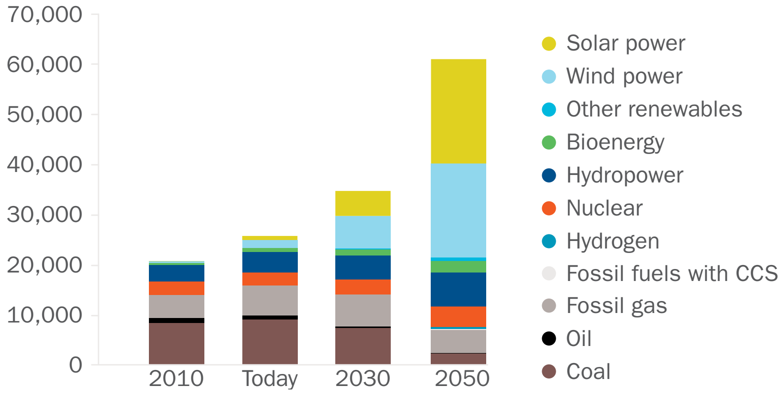
Solar PV is even more metal dependent than wind power due to the lower scale and less labour-intensive production. The elevated metal prices in recent months have increased solar module costs by more than one-third since early 2020. Even so, market prices for solar modules have increased by just 25 per cent as material efficiencies have improved and supplier margins are tight.

For batteries, the prices for nickel, lithium and cobalt all increased in 2021 due to a rapid increase in battery demand. This increase has been compounded by the supply chain effect of the Ukraine war, putting pressure on battery prices.
Raw material costs have increased by around 120 per cent for most cathode chemistries, and more than 330 per cent for the low cost LFP batteries (Lithium iron phosphate).[31] As a response to the high prices, auto-makers have been shifting to the low cost alternatives (LPF), or battery chemistries with higher nickel content.

Other cost items have also increased during the pandemic, for example wind turbine foundations, cables, electric equipment such as transformers and inverters, on-site buildings, fuel for transport, installation, and more. Together this means that prices are currently much higher than pre-pandemic which could have a negative short-term impact on the speed of the green transition. This could be counteracted by governments as long as new cost levels are reflected in support schemes and auctions for wind and solar until costs return to more normal levels. However, the current high fossil fuel prices have preserved and improved the competitiveness of renewable technologies compared to fossil technologies.

Although there are various types of supply risks for clean technology materials, there is, in general, ample resources available to cover future demand growth. Given the right price signals, along with government support, sufficient investment will stimulate supply growth. Long lead times for production could result in volatile metal prices in the years to come, but likely not enough to derail the energy transition.

8 Global electricity generation by source (TWh)



# A palette of renewable technologies needed

**In the Low Emissions Scenario, we see a doubling of power demand in 2050 compared to today, of which 80 per cent comes from renewable sources. Solar PV is the largest power generating technology, increasing 26-fold from today, followed by onshore wind, offshore wind and hydropower.**

In the Low Emissions Scenario, the world needs clean power to reduce emissions in all sectors and electrification must start in parallel to the decarbonisation of the power sector. On top of this, more than 700 million people still lack access to electricity worldwide, and high fossil fuel prices have pushed millions into energy poverty.[32] Reducing emissions from power generation while supplying the electricity needed in the future is an enormous challenge.

In sum, this results in roughly a doubling of power demand in 2050 compared to today (Figure 8).
To meet the power sector's need for fossil fuels, all renewable technologies are required, and per the Low Emissions Scenario, these renewable technologies will grow considerably towards 2050. Renewable energy will constitute almost 80 per cent of the total power generation in 2050, with wind and solar covering two-thirds. This will reduce coal and gas power generation by 75 per cent and 23 per cent, respectively.

Reaching these high levels of renewable power is technologically feasible, but the transition requires a political balancing act. Such a fast global transition will require public support, land availability, sufficient manufacturing capacity, skilled manpower, access to sustainable raw materials, strong grid infrastructure, all while maintaining a flexible and secure power system. However, alternative climate pathways are expected to be even more challenging, less efficient, and more costly.

Hydropower is the world's largest renewable electricity provider today and will have a key role in the energy transition going forward. In the Low Emissions Scenario, global hydropower generation will grow by 1.6 per cent per year on average from today to 2050, ultimately making it the fourth largest power generating technology globally after solar PV, onshore and offshore wind.

In the Low Emissions Scenario, solar power production increases 26 times to more than 21,000 TWh by 2050 and will be the largest source of power generation from 2035. This is possible because solar power is cost-competitive and flexible in terms of location, fast and easy to build compared to other technologies. This makes it a suitable technology to scale up quickly. Solar PV is therefore a main technology pushed forward by the EU that can help reduce reliance on Russian gas through the REPowerEU plan.

Onshore wind is currently the most affordable source of power in many parts of the world. Onshore wind power generation will grow almost eight times and culminate in nearly 11,500 TWh by 2050 in the Low Emissions Scenario. Turbine size for onshore wind will continue to grow from 1 MW in 2000, 4 MW today to around 10 MW in 2050. Onshore wind could affect a significant share of land and local resistance has delayed the growth in onshore wind capacity in some regions. In the REPowerEU plan, the European Commission aims to solve this by identifying "go-to areas" to shorten and simplify permit processes to reach the massive growth ambitions for onshore wind.

Compared to onshore wind power, offshore wind is generally more expensive, but has some other advantages, such as more stable production, bigger and more efficient turbines, and often less local resistance.

# Technologies for efficient land use

**Renewable technologies are relatively land intensive. Using land for energy production will entail compromises between local alternative use, and national and global climate and energy security needs. The negative externalities need to be minimised, the local communities need to be involved and the area usage must be optimised. Luckily, there are several technologies available that minimise total land-use needs for renewable energy.**

**Rooftop solar:** Mounting solar panels on rooftops or integrated in buildings is the most common practice for area efficient solar generation, and around 40 per cent of solar capacity in the Low Emissions Scenario is rooftop or other residential solar.

**Co-location of solar and wind generation:** Co-locating wind and solar generators has several benefits. The obvious one is that they can share the land with solar panels in between the turbines. In addition solar and wind can share grid connection, equipment, permitting procedures and workers. All while they are maximising capacity of the grid with complementing production.

**Floating solar:** Solar generation can also be installed on water. Floating PV can be installed on lakes, reservoirs, and other man-made bodies of water with little other use. Floating solar has not only land use advantages but is also usually more efficient compared to land based solar, since the water lowers the temperature under the panels. Floating PV on existing hydropower reservoirs offers additional benefits due to the complementarity of production profiles, reduction in grid connection and infrastructure costs, while also reducing water evaporation from the reservoirs, thereby conserving water resources for hydropower generation.[33]

**Agrivoltaics:** Solar generation combined with agriculture is also possible. This entails mounting the solar panels on stilts, allowing agricultural machinery to work beneath them. Crops beneath the panels are partially shaded during the day as the sun moves. Some crops handle this well, and under very dry conditions this could result in higher yields. As with floating solar, agrivoltaics could have efficiency benefits because of the cooling effect of the vegetation below the panels.[34]

**Offshore wind:** A solution for wind is to build generation completely off land. Wind speeds are generally stronger offshore and wind speed and direction are also more consistent. However, offshore wind could come in conflict with wildlife and fishery. Offshore wind is especially important in population dense areas of the world.

In the Low Emissions Scenario, offshore wind power generation increases 58-fold towards 2050 compared to today's level, reaching almost 8,000 TWh.

The biggest offshore turbines planned off the coast of China, coming online in 2026, have an expected capacity of 16 MW, with a height of over 260 meters and a rotor diameter of over 240 meters.[35] Western manufacturers are currently prototyping 14 and 15 MW turbines, and turbine growth is expected to continue.

The most mature and cost-efficient technology for offshore wind is bottom-fixed. This technology is suitable for areas with rather shallow waters and high wind, for example the southern parts of the North Sea, and areas on the east coast of the US and China. However, for much of the densely populated parts of the world, floating offshore wind will be important for decarbonising power production.

The floating technology is still in a pilot phase and accounts for only 0.1 GW of today's installed capacity, compared to around 53 GW of total offshore wind capacity installed globally.[36] Around 80 per cent of both global and European offshore wind potential is in deeper waters and requires floating technology.[37] For some countries the percentage is even higher, such as for Norway, South France, Scotland, Ireland, Spain, Portugal, Greece, Italy, South Korea, Japan, Australia, Taiwan, and the US west coast. Interest from governments and developers is record high with multiple floating auctions planned in the short-term. Many of these regions contain large population centres which could benefit from offshore wind energy and thereby contribute to advancing technology development. Also, wind speeds and stability are often higher in floating areas, which is positive for production.

In the Low Emissions Scenario, offshore wind power generation increases 58-folds towards 2050 compared to today's level, reaching almost 8,000 TWh. This will make offshore wind the third largest power generating technology globally, after solar PV and onshore wind.

# Temporary increase in coal use for short-term relief from fossil gas

**Fossil fuels and nuclear will continue to play a role in the power sector in the coming decades. Fast recovery from the pandemic and high gas prices last year led to the highest increase in coal power production ever. In the long run, both coal and fossil gas power will experience structural decline, and we end up with four per cent unabated coal and eight per cent fossil gas in the power generation mix in 2050, according to the Low Emissions Scenario. Nuclear will be pushed forward in some countries, resulting in a 60 per cent increase from today.**

Gas and coal generation are today the largest sources for power generation globally, responsible for 23 and 35 per cent of the power mix, respectively. High growth in electricity demand in Asia during the COVID-19 recovery resulted in a return to increased coal-use in the power sector in 2021. This led to the highest increase in coal power demand on record, after decreasing by seven per cent from 2018 to 2020.[38]
With record high power demand growth, coal consumption in China increased by 4.6 per cent in 2021. Despite this increase, the share of coal in the power generation mix has declined by 11 percentage points since 2010.[39]

High gas prices and security of supply concerns in Europe have made coal more acceptable in the short-term. As a response to Russia cutting gas supply to Europe, Austria, Germany, and the Netherlands, announced that they allow for increased coal power generation in 2022.[40]

Fossil gas in power generation is the most flexible of the fossil fuels and has been steadily increasing over the last decade - cutting emissions by replacing coal fired power generation. But with the surging gas prices, expected gas demand growth has taken a hit. This, combined with the falling costs of renewable technologies, results in a 23 per cent lower fossil gas demand in the power sector in 2050 compared to today, according to the Low Emissions Scenario.

With the Russian invasion of Ukraine and the current gas price crisis, Europe is expected to be more reluctant to build new gas power plants and gas demand from the power sector will decline more rapidly. Still, efficient gas peakers are expected to have a role in Europe the coming decades, until clean flexible technologies, such as hydrogen peakers, become more readily available.

The global policy push to phase out coal is increasing. In November 2021 at the annual UN climate negotiations, COP26, nearly 200 countries agreed to “accelerate efforts” to phase out “inefficient” fossil fuel subsidies, and the “phasing down” of unabated coal consumption.[41] This is a milestone in international negotiations even if greater ambitions and commitments are needed for a net zero pathway.

In 2050, coal power remains in a few coal countries in Asia, including China, India, and Indonesia. As coal is an integral part of society in these countries, creating jobs and enhancing energy security, more government support and regulation is needed for these countries to diversify and move away from unabated coal.

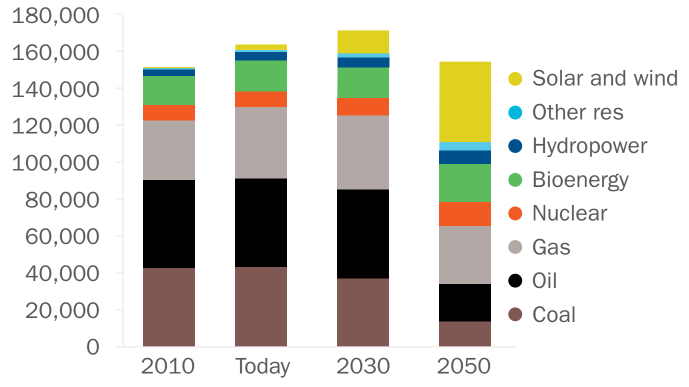
Carbon capture and storage (CCS) is a possible alternative for the large coal countries. But coal is an inefficient energy source, and contributes to local air pollution, in addition to being very carbon intensive. Towards 2050, CCS is expected to have a negligible role in the power sector as costs will be high compared to other emission-free alternatives. However, it is expected to play a role in cutting emissions from industry.

In 2050, we still end up with four per cent unabated coal and eight per cent fossil gas in the global power generation mix and fossil gas remains a key solution in many countries, needed to balance the increasing share of intermittent renewables towards 2050. However, the running hours for gas power is substantially reduced.

Nuclear power generation is experiencing a renaissance in some countries, such as Japan, France and South Korea.[42] Surging prices for fossil fuels, coupled with national security and climate concerns, has again put the spotlight on nuclear. However, many nuclear projects have been plagued with cost overruns and postponed start-ups over the last decades and they are currently facing a shortage of skilled staff. In the Low Emissions Scenario, we end up with more nuclear in the mix, an increase of 60 per cent in 2050 compared to today, primarily driven by growth in Asia.


High gas prices and the security of supply concerns in Europe have made coal more acceptable short-term.

9 Primary energy demand by energy source 2010-2050 in the Low Emissions Scenario. The primary energy demand is lower in 2050 as today, with more renewable in the mix (TWh)



# We will need less primary energy in 2050 than we do today

**For the first time, our analyses show lower primary energy demand in 2050 compared to today even with significant growth in the world economy and population. The energy mix is significantly different, with more renewables and less emissions.**

Primary energy refers to total energy needed, including transformation and distribution losses when converting to electricity, oil products and other useful energy forms that can be used in the end-use sectors.

Towards 2050, the current trend of decoupling economic growth and energy will continue. This means that the world will need less primary energy for providing the same value compared to today. This decoupling happens on three levels:

**Electrification:**
Direct use of electricity requires less energy compared to burning fossil fuels in most cases, meaning you will need less energy to produce the same service, work, or heat.

**Energy efficiency:**
Less energy spillage, more effective use of materials and recycling and behavioural changes across all sectors.

**Less energy intensive growth:**
As the world's economy becomes more developed, the economic growth will be more driven by the less energy-intensive service sector.

In addition, power generated from renewables requires less primary energy compared to power generated from coal and gas.[i] In sum this results in primary energy demand being somewhat lower in 2050 with a different energy mix and less emissions, compared to today, even with significant growth in the world economy and population (Figure 9).

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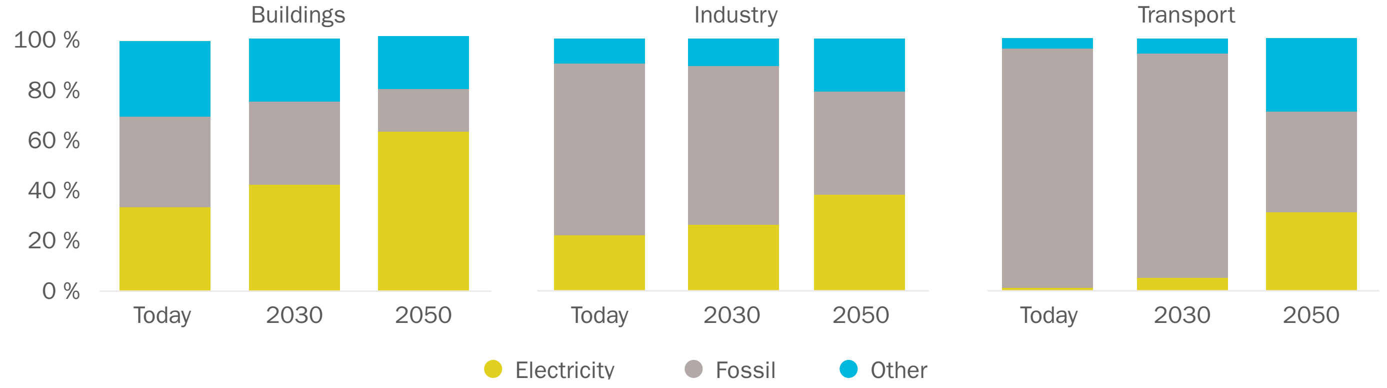
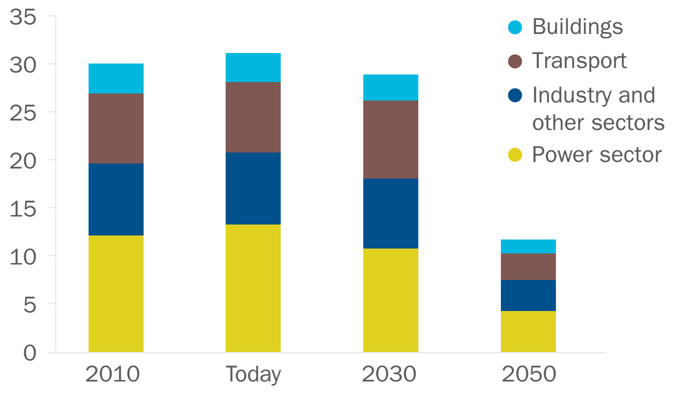
[i] The Low Emissions Scenario uses the IEA's calculation method. In primary energy calculations, zero losses are therefore assumed for renewable energy. With an alternative method that assumes approximately the same loss for fossil and renewable power production (38%), fossil fuels will cover around 30% of the primary energy in 2050 instead of almost 50%. However, the absolute amount of fossil fuels will remain unchanged regardless of calculation method.

10 Share of electricity and fossil fuels in buildings, industry and transport (%)



11 Global energy-related CO2 emissions by sector (Gt CO2)



# Electrification cuts emissions and saves energy

**Energy efficiency, electricity, clean hydrogen, and bio reduce emissions and fossil fuel dependency in the end-use sectors. The direct use of electricity combined with energy efficiency are deemed the most cost-efficient ways where feasible. As an example, heat pumps can deliver two to five times more heat than the electricity they consume, consequently cutting emissions, energy and costs.**

Both transport and industry are today heavily reliant on fossil fuels (Figure 10). Oil is by far the most preferred fuel in transport, and industry is fossil fuel-intensive. Even though buildings have a lower fossil share, the heating sector is heavily reliant on fossil gas. Many countries in the world are dependent on imports of fossil fuels, hence replacing fossil fuels with electricity is an important step on their way to energy-independence, resulting in reduced exposure to volatile fossil fuel prices, while also cutting emissions.

In the Low Emissions Scenario, emissions are reduced by more than 60 per cent by 2050 (Figure 11). Energy efficiency, electricity, clean hydrogen, and bioenergy are a means for reducing emissions and dependency on fossil fuels in the end-use sectors. The direct use of electricity along with energy efficiency are deemed the most cost-efficient ways of cutting emissions where feasible. Electricity is an efficient energy carrier, as it cuts emissions, it provides flexibility to the power system, and it improves air quality.

## Decarbonising the buildings sector with heat pumps and more efficient use of energy

Ten per cent of global energy-related CO2 emissions are due to the use of fossil fuels in heating and cooking in buildings.[43] Fossil gas is widely used for both space heating, hot water and cooking in many parts of the world. In some parts, oil and even coal is also used. Traditional biomass is typically used in poorer countries (e.g. wood burning or open fire cooking).

Energy for heating is the main source of emissions in the building sector. To decarbonise heating, electricity can be used directly to generate heat via electric heaters or boilers, or through heat pumps, thereby replacing fossil fuels.

Energy efficiency in buildings, both in insulating the building mass, in appliances and with the use of heat pumps, is an important and a cost-efficient contribution to reducing greenhouse gas emissions.

### HEAT PUMPS ARE AN EFFICIENT TOOL FOR CUTTING EMISSIONS AND FOSSIL GAS-USE IN BUILDINGS

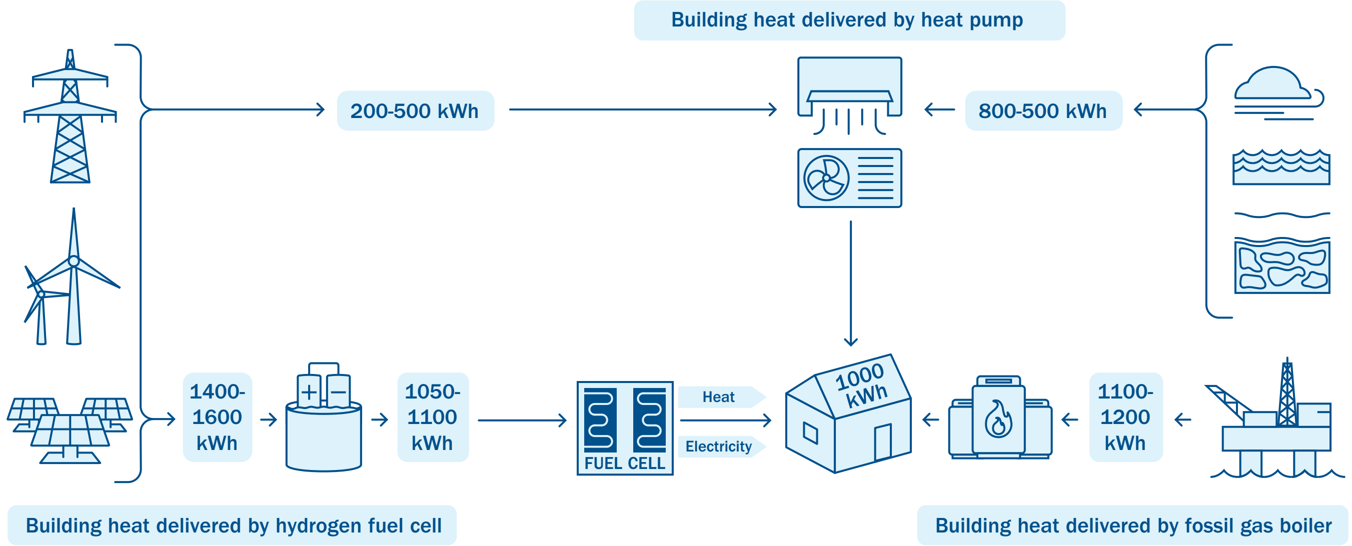
Heat pumps are very efficient due to their ability to extract heat from the air, water, or the soil, ultimately delivering more heat overall than through direct electricity. Depending on the heat content in the environment, heat pumps can deliver two to five times more heat than the electricity they consume, consequently cutting both emissions, energy and subsequently costs as well (Figure 12).

The large energy gains and emissions cuts combined with the current high energy prices are leading to a heat pump revolution in Europe.
The buildings sector accounts for one third of the gas used in EU, and heat pumps are an important tool in the EU's REPower plan to cut dependence on Russian gas.[44]

### ENERGY EFFICIENCY KEY TO EMISSION REDUCTIONS IN THE BUILDINGS SECTOR

Investments in energy efficiency measures in buildings are increasing. Investments increased by over 11 per cent in Europe in 2020 to about USD 184 billion, mainly due to EU governmental support.[45] However, the investment amount needed globally is much larger. The EU renovation goal alone requires EUR 275 billion

12 Illustration of energy needed to deliver 1000 kWh of heat based on hydrogen, heat pumps and fossil gas boilers.



in extra support each year, according to the Green Finance Institute.[46] Sufficient investment in upgrading building mass will need government support, as well as updated codes and standards. This does not, however, eliminate the need for large behavioural changes in the building sector with regards to when and how much energy is used.

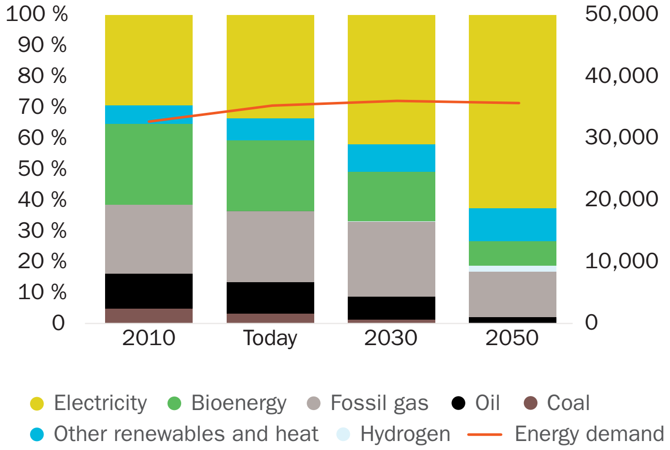
### THE LOW EMISSIONS SCENARIO CUTS EMISSIONS WITH ENERGY EFFICIENCY AND ELECTRIFICATION

Despite economic growth, more urbanisation and greater access to energy, the increasingly efficient use of energy results in a constant energy demand level in buildings throughout the period to 2050. Electricity demand from the buildings sector almost doubles over the same period, replacing coal, gas, oil and use of traditional biomass (Figure 13). This results in a decline in $CO_2$ emissions of 55 per cent from today to 2050, while electricity share in final energy demand increases from 33 to 63 per cent.

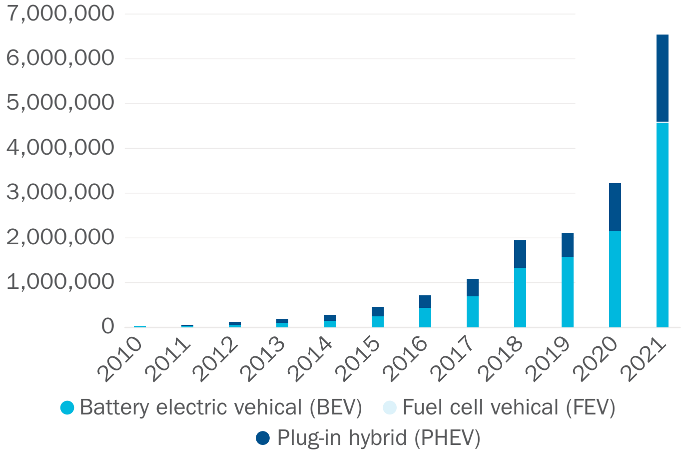
Clean hydrogen is a less efficient decarbonisation measure in buildings, and the uptake is expected to be limited. However, clean hydrogen can be a niche solution in areas where the grid infrastructure is weak or where existing gas infrastructure can be reused for hydrogen.

↑ Energy efficiency in buildings, both in insulating the building mass, in appliances and with the use of heat pumps, is an important and a cost-efficient contribution to reducing greenhouse gas emissions.

13 Global energy demand for buildings by energy carrier (%) and total energy demand (TWh)



14 Historic global yearly electric car sales (vehicles)[50]



## Decarbonising the transport sector with electricity and hydrogen

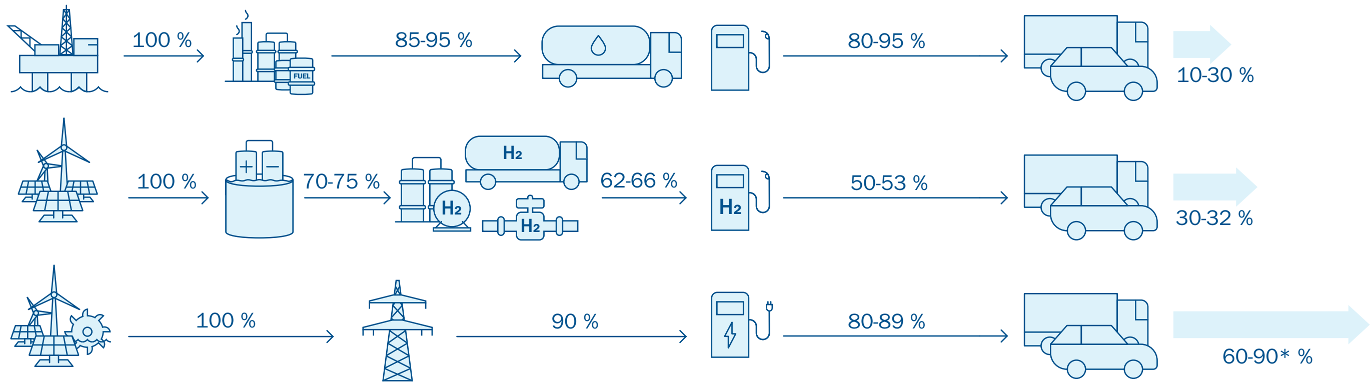
Transport is responsible for approximately 20 per cent of global energy-related $CO_2$ emissions today with road transport accounting for around three-quarters of transport emissions. The remaining transport emissions are from shipping, aviation, and rail. More than half of road transport emissions come from passenger light-duty vehicles.[47]
We expect an accelerated uptake of electric passenger cars globally resulting in passenger cars becoming predominantly emissions-free by 2050.

### POSITIVE SIGNS FOR ELECTRIC VEHICLES DESPITE PANDEMIC AND WAR

The disrupted supply chains from the global COVID-19 pandemic and the war in Ukraine have significantly impacted the car industry. However, there are still several positive signs for the future growth in electric vehicles (EV) sales. In 2021, public spending on subsidies and economic incentives nearly doubled compared to 2020. Many carmakers have ambitious target for EV implementations, and the number of available EV models has increased fivefold since 2015.[48]

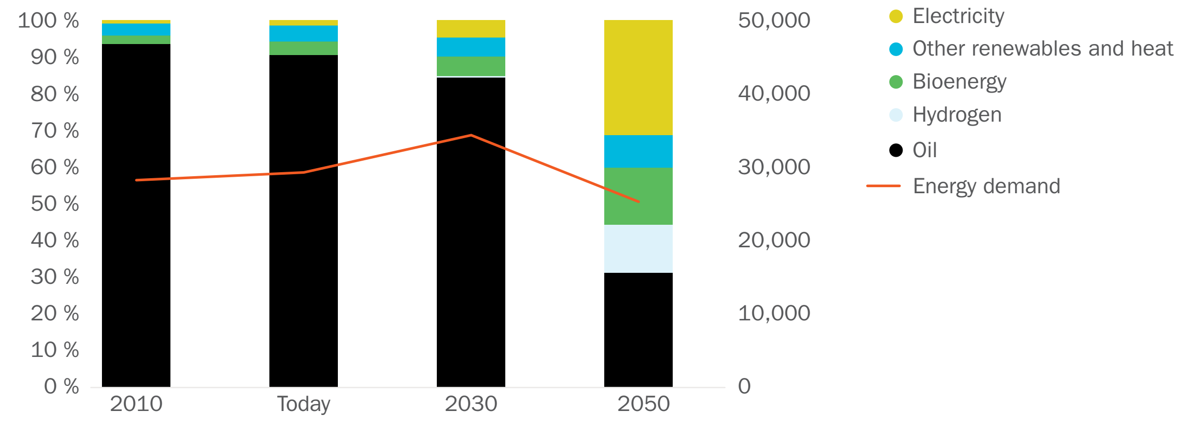
In 2021, new electric cars more than doubled compared to the year prior, resulting in 6.5 million new electric cars on the road (Figure 14). Electric cars accounted for nine per cent of global car sales in 2021. China is in the lead, tripling its electric car sales and accounting for more than 50 per cent of global sales, followed by Europe and North America. The highest share of electric car sales last year was in Norway with 72 per cent, and Sweden and Netherlands, with 45 and 30 per cent respectively. Global electric car sales continued to grow in the first two quarters of 2022, up more than 60 per cent compared to a year earlier.[49]

15 Illustration of energy losses for battery electric vehicle (EV), hydrogen fuel cell vehicle (HFCV) and internal combustion engine (ICE)



*lower end is without recovering mode on the electric cars

16 Global energy demand from the transport sector by energy carrier (%) and total energy demand (TWh)



In the Low Emissions Scenario, costs for electric cars are expected to continue declining, despite current supply chain issues for raw materials in batteries. With the continued cost decline for batteries, we expect average battery-powered electric vehicles to reach cost parity within the next few years with some variation between regions and car type and models. This is expected to further accelerate sales of electric vehicles.[51]

### CUTTING EMISSIONS AND DEPENDENCE ON OIL IN PASSENGER TRANSPORT

According to the Low Emissions Scenario, the global passenger vehicle fleet is all electric in 2050, with some fuel-cell hydrogen cars in niche applications. As an electric car only uses around one-third of the energy of a traditional internal combustion engine (Figure 15), electric cars displace around 20 million barrels per day of oil demand by 2050. For reference, total global oil demand is around 97 million barrels per day, with transport accounting for around 60 per cent of this demand.

### HYDROGEN NEEDED IN HEAVY ROAD TRANSPORT, SHIPPING AND AVIATION

However, oil is not only used in passenger cars. It is also used in heavy road transport, shipping, and aviation, which combined is responsible for more than 40 per cent of $CO_2$ emissions from transport today.[52] Heavy-road transport can switch to battery electric vehicles for shorter distances and urban areas. But batteries will not provide sufficient range for long-haul road transport, which is when clean hydrogen or biofuel will be needed. In the Low Emissions Scenario, half of new trucks will be emissions-free in 2050, while the remaining share is expected to be a mix of hybrid-fuelled trucks, bio-blends, and some fossil gas.

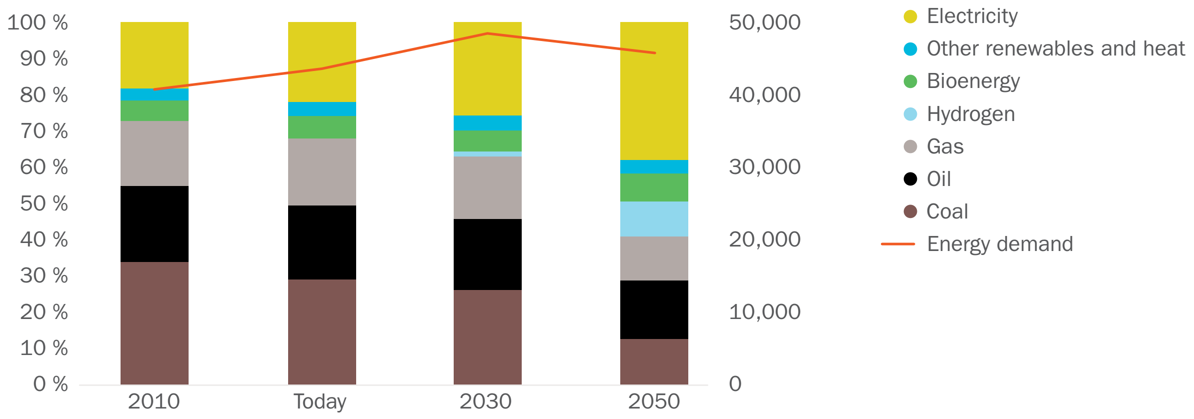
Clean hydrogen will also be important in cutting emissions in aviation and shipping, most likely in the form of clean ammonia or e-fuels. In the Low Emissions Scenario, we expect that the maritime sector will decarbonise by fuel switching from heavy fuel oil to LNG, biofuels, electricity, clean ammonia, and e-fuels combined with operational and efficiency measures. Ammonia is likely to become a key solution for long distance maritime freight towards 2050, while e-fuels, such as e-methanol, play a key role in aviation. For both shipping and the aviation sector, shorter local and regional routes can be electrified.

### ELECTRIFICATION REDUCES EMISSIONS AND ENERGY USE IN TRANSPORT

By 2050, the emissions from the transport sector will be reduced by around 63 per cent compared to today, while electricity share in final energy increases from 1 per cent to 31 per cent in the Low Emissions Scenario (Figure 16). All transport segments will become more efficient. It will require less energy to transport the same goods and people, while the underlying demand for mobility is expected to grow. Passenger vehicles, including the smaller 2/3-wheelers, will be predominantly electric and emission-free, and the remaining emissions will come from long-distance transport between countries and continents.

In 2021, new electric cars more than doubled compared to the year prior, resulting in 6.5 million new electric cars on the road.

**17** Global energy demand from the industry sector by energy carrier (%) and total energy demand (TWh)



## Decarbonising the industry sector

The industry sector is energy and emission intensive and accounts for about 24 per cent of energy-related emissions globally.[i,53] Parts of the industry sector are challenging to decarbonise through direct use of electricity and are referred to as hard-to-abate. In the industry sector, the hard-to-abate part is mostly heavy industrial processes that demand heat over 500°C, such as the cement, iron and steel and chemical sectors.

Clean hydrogen, bioenergy, and CCS, in addition to energy and material efficiency, are needed to cut emissions in the hard-to-abate sectors, while technologies for electrifying high-heat processes are only in the development phase.

### DIRECT USE OF ELECTRICITY FOR LOW TEMPERATURE HEAT

Around half of the heat used in industry can be categorised as low temperature (below 200°C). In these cases, a variety of decarbonisation options exist. Heat pumps and electric boilers can replace thermal processes that are commonplace in many industries. This equipment can be retrofitted to existing machinery and hybrid systems can be installed. Electrification using heat pumps where possible will also improve efficiency.

### RECYCLING AND MORE EFFICIENT USE OF MATERIALS AND ENERGY

In general, material and energy efficiency gains are the most cost-efficient ways to reduce energy related emissions and energy consumption in industry. Lifetime extensions of buildings, improved design, and manufacturing techniques, along with light weighting[ii] are among other important measures.

Recycling is well established within metals, plastic, glass, and paper. Recycled plastic saves 50-60 per cent in greenhouse gas emissions compared to normal plastic production. For recycled steel produced using electric arc furnaces, the entire process uses only 20-25 per cent of the energy used to produce primary steel. If the electricity used for the furnace is renewable, it could be virtually emission-free.

### HYDROGEN, CCUS AND SUSTAINABLE BIO FOR HARD-TO-ABATE SECTORS

For iron and steel production, replacing coal and fossil gas with emission-free hydrogen could lead to a more efficient process, and cut both energy-related and process emissions at the same time. For cement, one possibility is to shift from coal to sustainable bioenergy, or to use CCUS (Carbon Capture, Utilization and Storage) to cut emissions. CCS together with sustainable bio will result in negative emissions, a requirement for reaching net zero. For the chemicals industry, the use of clean hydrogen for ammonia production can replace the fossil hydrogen in use today, thus stimulating value chains for clean ammonia to also fuel the transport sector in the future.

### NUMEROUS TECHNOLOGIES ARE NEEDED TO CUT EMISSIONS IN INDUSTRY

In the Low Emissions Scenario, the energy consumption in the industry sector is falling after 2030 despite underlying economic growth (Figure 17). This is a result of energy efficiency gains, more efficient use of materials and a high share of recycling. Combined with electrification, emission-free hydrogen and some CCUS, there is a reduction in energy-related emissions from industry of 55 per cent by 2050 versus today.

Electrification of industry will take time globally, and the Low Emissions Scenario assumes a gradual electrification towards 2050. By 2050, 38 per cent of the global energy demand from industry will be met by direct use of electricity.

← In the industry sector, the hard-to-abate part is mostly heavy industrial processes that demand heat over 500 °C, such as the cement, iron and steel and chemical sectors.

↓ Recycling is well established within metals, plastic, glass, and paper. Recycled plastic saves 50-60 per cent in greenhouse gas emissions compared to normal plastic production.

Clean hydrogen will also be an important tool for decarbonising industry, around 10 per cent of the energy demand met by emission-free hydrogen by 2050. This will replace gas and coal for chemical feedstock, steel production and other high temperature heat. Timing is important for clean technologies as industrial plants being built today risk locking in emissions for the next 40 years.

In the Low Emissions Scenario, the dynamic between climate and energy policies, markets and technology costs, are driving the decarbonisation in the buildings, transport, industry, and power sectors. Currently, energy security has moved up on the policy agenda across the globe and will play a key role going forward. The role of energy security in driving the transition is further discussed in the next chapter, where we also analyse Europe and the REPowerEU plan in more detail.

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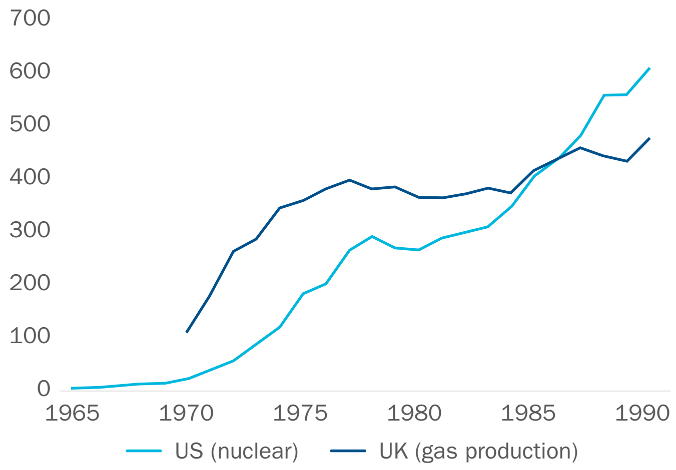
[i] This includes emissions from the combustion and production of heat for industrial processes. The emissions include emissions from iron and steel production, the chemical and petrochemical industry, cement and the pulp and paper industry.

[ii] Reducing the weight of cars and trucks in order to reducing the material required.

18 Nuclear generation in the US and gas production in UK (TWh)[54]



# Energy security policies drive the energy transition

**Energy security has always had a key role in energy policy. With the current energy crisis and war in Ukraine, energy security has again moved up on the policy agenda around the world. In Europe, this has materialised in the REPowerEU plan which includes the dual ambitions of becoming 100 per cent independent of Russian fossil gas while reaching the 55 per cent climate target by 2030.**

Energy security has a major role in energy policy, and former energy crises have been a main driver of shaping the energy world we see today. In response to the global energy crisis of the 1970s, many countries made major shifts in their energy investments (Figure 18).[55] Deployment of nuclear energy was accelerated and the US invested in almost every energy source imaginable - from coal, nuclear and unconventional oil and gas production to solar panels, wind turbines, and energy efficient technologies. The UK broke its dependence on coal by making large investments in North Sea gas. Similarly, an energy crisis of today's magnitude can once again trigger a powerful shift in energy systems globally to low-cost renewable resources that are readily available.

Such a powerful shift could take place in Europe with the REPowerEU plan, launched by the European Commission in May 2022. The plan is an emergency response to the Russian invasion of Ukraine and elevated gas prices. It builds on the EU's Green Deal and "Fit for 55" legislative package which provide the strategy and framework for how to reach the 2030 and 2050 climate targets. This in itself is an enormous transformation of the European energy systems.[i,56] The REPowerEU Plan is an emergency plan to rapidly reduce Europe's dependence on Russian gas imports by diversifying supply while accelerating energy efficiency, electrification, hydrogen, and renewables deployment. This serves both energy security and climate targets.

The REPowerEU plan is followed by several Member State initiatives. France has increased its ambitions for nuclear expansion to reduce its dependence on Russian energy. Germany has taken a political U-turn, suspending the new pipeline between Russia and Germany (Nord Stream 2), and instead building four floating regasification units (FSRU) in order to import LNG and diversify their gas supply mix. Germany also plans to go 100 per cent renewable by 2035 in the power sector, with the share of wind and solar power reaching 80 per cent by 2030. The German Finance Minister Christian Lindner referred to renewable electricity sources as "the energy of freedom".[57]

**↓ The REPowerEU plan is followed by several Member State initiatives. France has increased its ambitions for nuclear expansion to reduce its dependence on Russian energy.**

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[i] The "Fit for '55 package" consists of twelve legislative proposals, two thirds of which are updates or revisions of existing legislation, covering the EU emissions trading system (ETS), member stats emissions reduction targets for non-ETS sectors, transport sector, energy efficiency, renewable energy, emissions from land-use, a social climate fund, energy taxation and a Carbon Border Adjustment Mechanism (CBAM).

DEEP DIVE

# REPowerEU – possible European pathways to reduce Russian gas dependency towards 2030

The European Commission launched the REPowerEU plan only weeks after Russian forces entered Ukraine in February 2022. Here we analyse different paths for the EU to shift away from Russian fossil gas before 2030. All scenarios see a rapid build-out of solar and wind power and higher share of electricity use in industry, buildings and transport compared to pre-war expectations. Also, import of fossil gas from other countries and demand for coal increase compared to a pre-war scenario. The ambition of reaching ten million tons of domestic green hydrogen within eight years looks extremely challenging and will require significant policy push and support, according to our analyses.

The Russian invasion of Ukraine has resulted in high fossil fuel prices and the threat of energy shortage and rationing. This has prompted a policy push in Europe through the REPowerEU plan, to accelerate the energy transition and cut dependence on Russian energy. To shed light on how Europe can fully shift away from Russian fossil gas dependency, we have analysed several possible pathways towards 2030. These pathways are then compared with the status today, with pre-war expectations, and with the REPowerEU proposed targets as outlined by the European Commission.[58]

The REPowerEU plan aims to increase EU's security of supply by focusing on the following three pillars:

- **Diversifying gas supplies**
  This includes increasing the pipeline imports from non-Russian suppliers (e.g., Azerbaijan and Norway), increasing LNG imports, joint gas purchase, an action plan for bio methane, and increasing the hydrogen target

- **Accelerated rollout of renewable energy**
  A massive upscaling and acceleration of renewable energy in power production, industry, buildings, and transport. This includes a huge roll-out of solar PV, with focus on solar panels mounted on buildings. Renewables go-to-areas for one or more types of renewable energy sources are planned to accelerate the permit-granting process. EU is proposing to increase the 2030 renewables target from 40 to 45 per cent

- **Saving energy**
  Focusing on behavioural changes, energy efficiency improvements, and electrification of buildings (with heat pumps), transport and industry. The 2030 target for energy efficiency is proposed to increase from 9 to 13 per cent.[59]

In 2021, the fossil gas imports from Russia were 155 bcm[i], covering around 40 per cent of EU's annual gas demand. Imports vary over time and were as high as 195 bcm in 2019.[60] In addition, the EU's domestic gas production is declining, increasing the need for imports.

Compared to the Green Deal and the "Fit for 55" package presented by the European Commission, the REPowerEU plan aims to go faster and further with clean energy projects. However, it is very hard to eliminate Russian gas imports overnight.

The REPowerEU plan is therefore divided into short-term, mid-term, and long-term measures.

**Short-term** measures will start immediately and focus on gas diversification and demand-side actions: increased non-Russian LNG and pipeline imports, coal power and nuclear extension, fuel switch and energy efficiency (heat pumps and savings from turning down heating). Industry curtailment if needed

**Mid-term** measures cover the period up to 2027 and include investments in new infrastructure such as LNG, gas pipelines, grid development and reinforcements. Electrification with large PV and wind additions and use of biomass for power production, battery storage, energy efficiency, even more heat pumps, production and use of sustainable bio-methane

**Long-term** measures: Hydrogen value chains with renewable hydrogen production and distribution systems.

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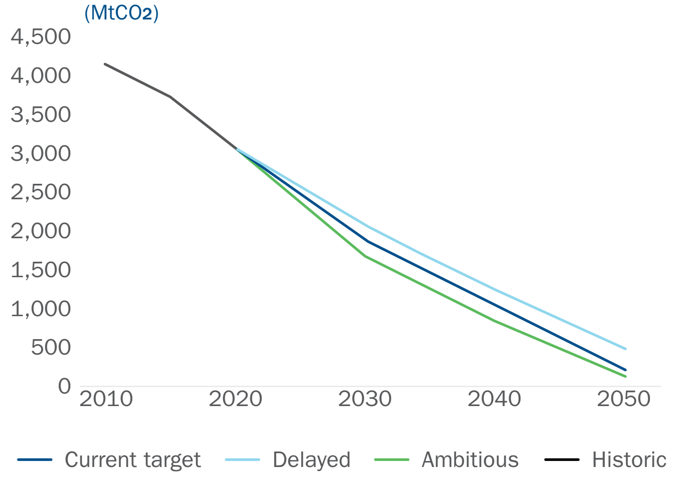
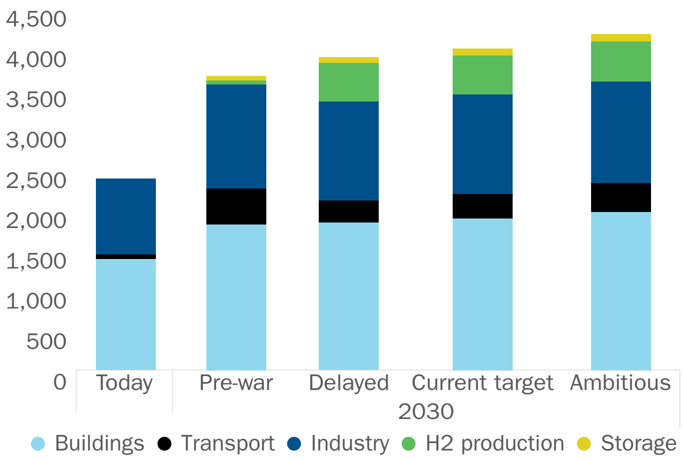
[i] bcm = Billion cubic meters of natural gas. Bcm is a unit of energy, often used in relation to production and distribution of natural gas and equals 10.47 TWh Including LNG imports

19 Historic $CO_2$ emissions from combustion of fossil fuels for EU27, Norway, Switzerland, and the Balkans (2010 – 2020) along with emission pathways showing different levels of climate ambitions ($MtCO_2$)



20 Use of electricity (in TWh) per sector for each scenario compared to todays' values



## Different climate pathways to 2050– scenarios for REPowerEU ambitions

The REPowerEU measures are based on the EU's 2030 goal to reduce emissions by 55 per cent compared to the 1990 level, and to reach net zero in 2050. To better understand the different solutions for the European energy transition across sectors, we have analysed **three different emissions pathways**: i) a **55 per cent** emission reduction target in 2030 (**'Current target'**), ii) **60 per cent** emission reductions in 2030 (**'Ambitious'**) and iii) a delayed target with **50 per cent** emission reductions in 2030 (**'Delayed'**) (Figure 19).[i]

Along these three emissions pathways, we have added the REPowerEU ambitions of becoming fully independent of Russian fossil gas imports before 2030.[61] In addition, we have looked at a pre-war cost-efficient scenario for reducing emissions by 55 per cent, without any fossil gas reduction targets (**'Pre-war'**). With this in mind, we have modelled and analysed four scenarios (**Pre-war, Current target, Ambitious and Delayed**), and then compared the results to the proposed targets in REPowerEU, as outlined by the European Commission ('REPowerEU').

## Electrification reduces fossil gas demand

Our analyses show that switching from fossil fuels to direct use of electricity ("electricification") is a key factor in reaching the 2030 emission reduction target, but also the most cost effective way to reduce dependence on fossil gas, along with energy efficiency. For all scenarios significantly more electricity is used in 2030 as compared to today (between 54 and 76 per cent more) – reducing gas demand in the different end use sectors. To become fully independent on Russian gas, the largest increase in electricity demand can be found in the industry sector, and the buildings sector compared to today, mainly due to the increased use of heat pumps (Figure 20).

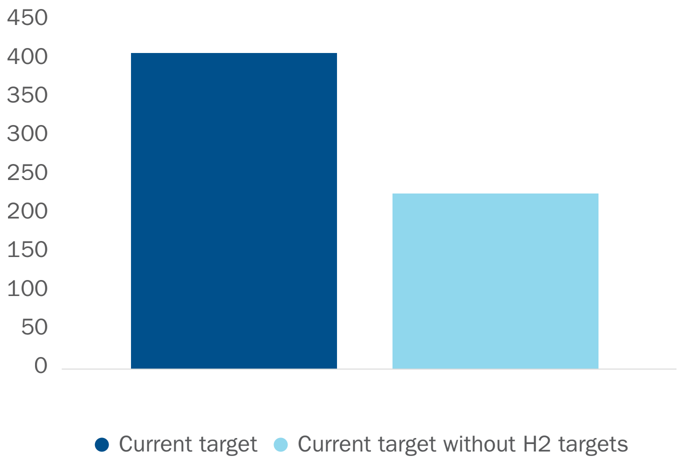
## The REPowerEU hydrogen target needs to be supported by policy

Even though direct use of electricity in the end-use sector is preferred, increasing the use of renewable hydrogen is essential to reduce emissions in cases when electrification is not feasible. Without policy push, green hydrogen as a climate solution is expected to begin accelerating after 2030.

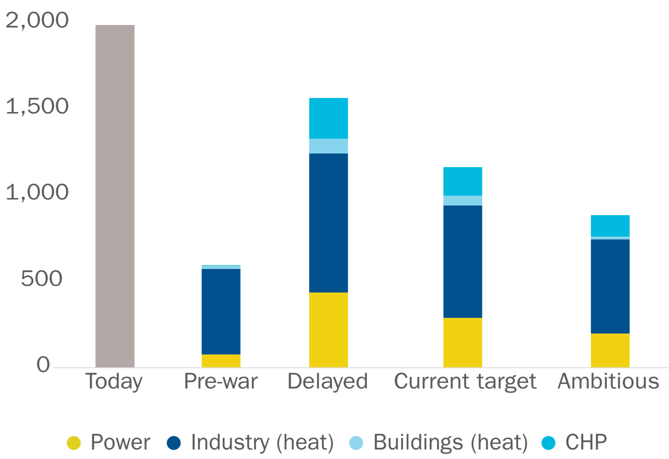
The new targets for green hydrogen in REPowerEU are ambitious with 10 million tonnes (Mt) of domestic production and 10 Mt of (green and blue) imports covering a total targeted yearly demand of 20 Mt of hydrogen already by 2030. This is a fourfold increase from the pre-war ambitions. Delivering on REPowerEU will require a domestic electrolyser capacity between 65 to 80 GW, where the spread is due to the number of running hours assumed for the installed electrolysers. The rest needs to be imported and assumes blue and green hydrogen investments outside EU, including transportation.[ii]

In our modelling, imported and domestically produced green hydrogen is mostly used for industry, by replacing fossil gas in heating, for feedstock replacing fossil based hydrogen, and directly in boilers. Hydrogen is to some extent also used for the transport sector, while a negligible share goes into power production. In our analysis, clean hydrogen will displace fossil gas rather than oil in all REPowerEU scenarios compared to pre-war, thereby shifting clean hydrogen use from the transport to the industry sector. Hydrogen is generally a less efficient way of cutting emissions compared to direct use of electricity. When modelling a cost-optimal European pathway, the ambitious EU hydrogen target of 20 Mt is not cost-optimal by itself and it will therefore not be achieved without significant political will and support within the EU.

21 The use of hydrogen for energy in the Current target scenario with and without hydrogen constraints (TWh). The use of hydrogen for feedstocks is not included



22 Total coal demand in 2030 (TWh)



If we compare the Current target scenario with and without the ambitious REPowerEU hydrogen targets, we see a significant difference in the use of hydrogen (Figure 21), especially for reducing gas demand in industry. With a more ambitious hydrogen target – less electrification is needed in all sectors. However, in total, this leads to higher power demand and overall higher costs, as there are efficiency losses in the production and use of hydrogen.

## Fossil gas phase-out increases coal demand

The REPower measures will contribute to a faster phase-out of Russian fossil gas, but will have a significant effect on the European energy system. In total, coal demand increases to 2030 compared to pre-war assumptions across all sectors and in all scenarios in our modelling (Figure 22).

The projected electrification and renewable hydrogen production increases power demand by between nine and 14 per cent compared to pre-war. Coupled with the dual goal of phasing out Russian fossil gas and cutting emissions, this will require a huge increase in renewable power capacity. However, with a high amount of variable renewable capacity and less fossil gas available in the mix, more coal is used as a flexibility provider in the power sector towards 2030 in the three scenarios compared to pre-war. To reach climate targets, the coal-use increases the need for renewable capacity, electrification and hydrogen to offset increased emissions from coal-use.

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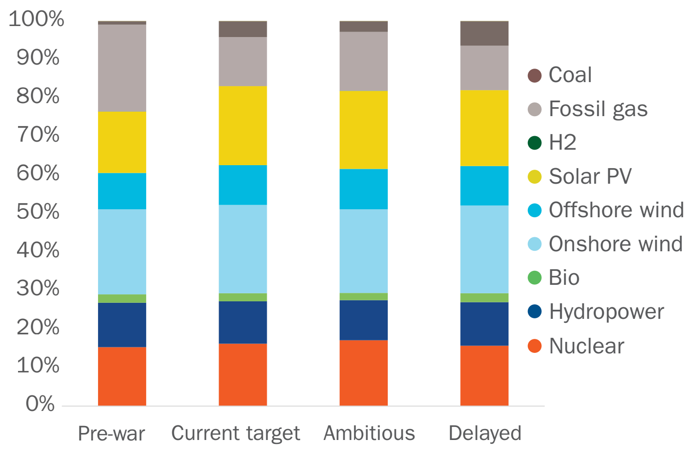
[i] See Annex 3 for model description

23 Electricity generation share by technology in 2030 for the four scenarios



## Substaintial increase in renewables needed across all scenarios

A phase-out of Russian gas coupled with increased use of coal power, electrification and green hydrogen will increase the installed power capacity and the renewable share in the power sector substaintially.

The REPowerEU plan has an indicative value of 69 per cent renewables as a target for 2030 which is a significant increase from the 38 per cent today. This is slightly higher than our analysis, showing a renewable share of 61 to 67 per cent across the four scenarios, the lowest share is the result of pre-war expectations, while around a two-thirds renewable share are reached in the three REPowerEU scenarios. Even if total power demand and renewable capacity increase in line with higher climate targets, the renewable share in the power generation mix remains fairly stable across the three scenarios. It is cost-optimal to cut emissions by electric heat pumps in buildings from gas power rather than using gas for heating. Also, the build out of new renewable capacity takes time and fossil gas is still needed in EU in 2030 to balance the renewable dominated power systems. Coal share in power increases by 2 to 5 per cent compared to pre-war expectations.

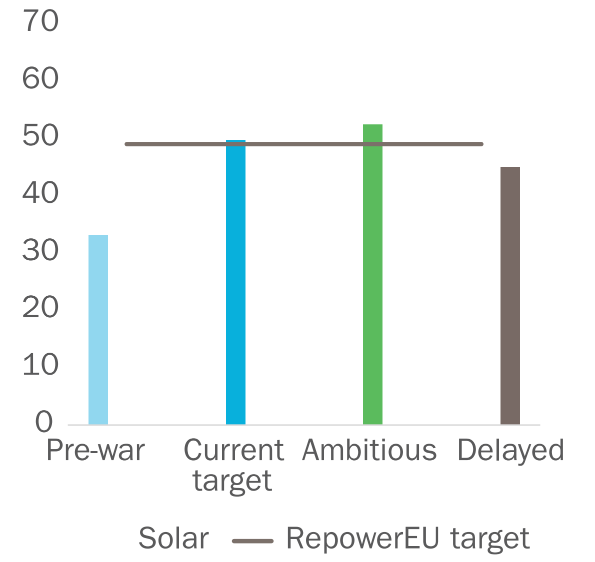
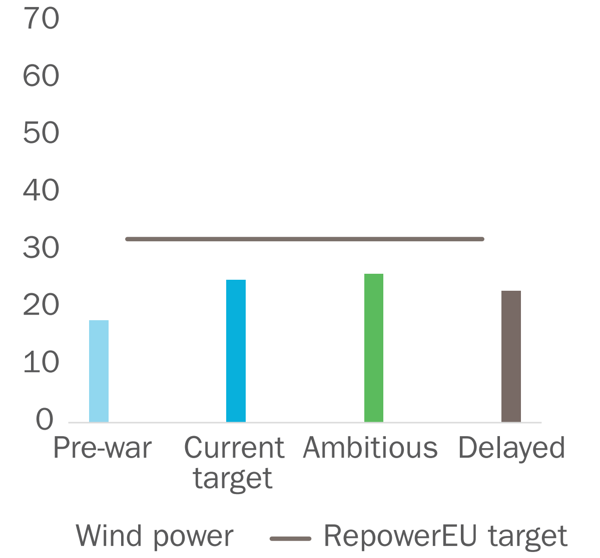
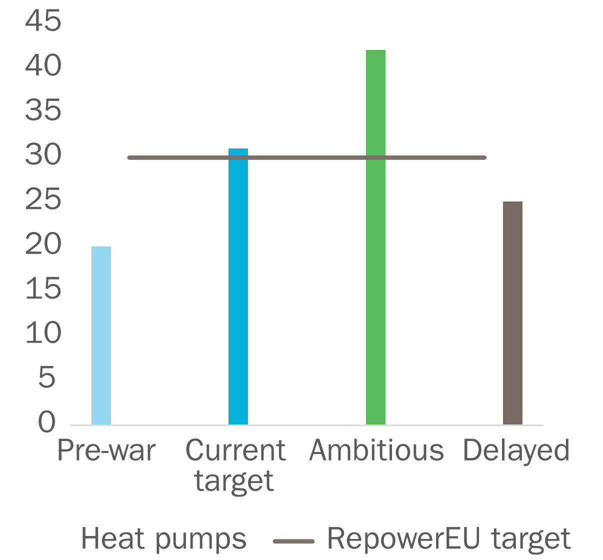
In all cases, solar PV and onshore wind become the two dominant sources of electricity generation. There's also a substantial increase in offshore wind capacity. Consequently, emission reductions in the power sector are driven predominantly by these technologies (Figure 23). Hydropower remains the third largest renewable electricity generating technology in all cases.

## Solar PV and heat pumps are the winners

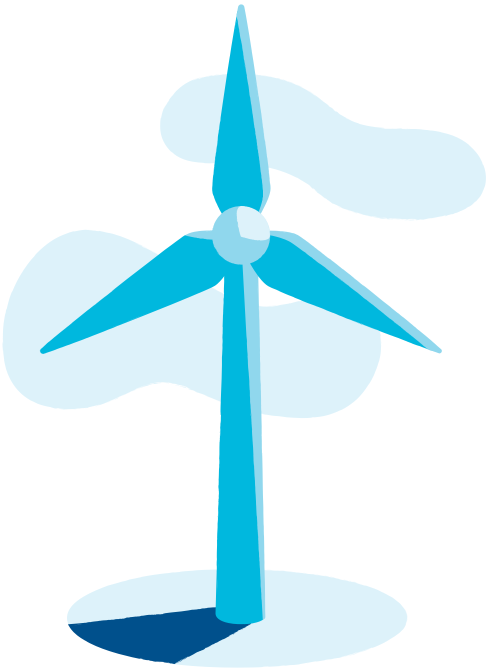
The REPowerEU target indicates a tripling of the installed capacity of solar PV and wind power within EU by 2030. Our analyses show that substantially more solar is needed in all our scenarios compared to pre-war expectations. Although 2021 was an all-time high for European solar, with a capacity addition of around 26 GW within EU, we see a yearly increase of 45 to 52 GW capacity needed towards 2030, significantly higher than the 33 GW per year expected pre-war. Compared to other technologies, it is easier to ramp up the solar PV capacity in Europe quickly, since the average development and construction time is typically less than two years. Also, the solar PV market already has an effective global supply chain, albeit heavily dominated by China.

The announced REPower targets for wind power are not reached in our scenarios. Even in our Ambitious scenario, we only reach a wind power capacity around 17 per cent lower than the EU target, as solar PV is preferred in our modelling.  To reach the targeted wind

24

| **Yearly capacity increase to 2030** | **REPower indicative target** | **Statkraft modelling results** | **Illustration** |
|---|---|---|---|
| **Solar power (GW)** | **49 GW** yearly capacity additions (leading to 600 GW installed by 2030) | **33 to 52 GW** yearly capacity additions |  |
| **Wind power (GW)** | **32 GW** yearly capacity additions (leading to 510 GW installed by 2030) | **18 to 26 GW** yearly capacity additions |  |
| **Heat pumps (millions)** | **30 million new electronic heat pumps** installed before 2030<br>[i] Assuming an average heat pump capacity of 11.9 kW. | **20 to 42 million new** electronic heat pumps installed by 2030 |  |

Currently, Europe is a global leader in offshore wind development, and this technology represents a huge opportunity for not only strengthening the security of supply, but also for reaching ambitious climate targets while retaining industrial leadership and creating jobs.



power capacity, governments must prioritise capacity additions and drastically increase permitting efforts.

In many areas, the cost of onshore wind power is lower than competing fossil fuel technologies. It is not necessarily the costs that limit further expansion, but rather constraints related to local acceptance, land use and permissions. The surging energy prices and the war in Ukraine could boost local acceptance for renewable technologies, especially compared to dependence on unstable regimes for the energy supply. However, in many European markets, obtaining an onshore wind permit can take up to seven years, which typically is the longest part of the development process. Simplifying permit processes is one of the key priorities in the REPowerEU plan.

Offshore wind can only be ramped up if supply chains are strengthened and expanded rapidly. Also, it takes typically around six to ten years to develop and build an offshore wind project, making it less suitable to scale up by 2030. Currently, Europe is a global leader in offshore wind development, and this technology represents a huge opportunity for not only strengthening the security of supply, but also for reaching ambitious climate targets while retaining industrial leadership and creating jobs.

Heat pump is an efficient technology for cutting gas demand in the building and industry sector and is a key priority in the REPowerEU plan. The REPowerEU target for buildings is 50 per cent higher than the cost optimal number of heat pumps in the pre-war scenario in our modelling. However, in two out of three REPowerEU scenarios, we end up with more heat pumps needed compared to the REPower target to reach the dual goal of cutting emissions and fossil gas-use. Also, with higher climate ambitions comes a greater need for heat pumps in buildings. In the Ambitious scenario, gas demand from gas boilers is reduced with 609 TWh compared to pre-war, while heat produced from heat pumps increases by 524 TWh. By using only 163 TWh electricity to produce this heat, this shows the enormous potential of heat pumps to reduce fossil gas use in buildings, while using the electricity more efficiently.

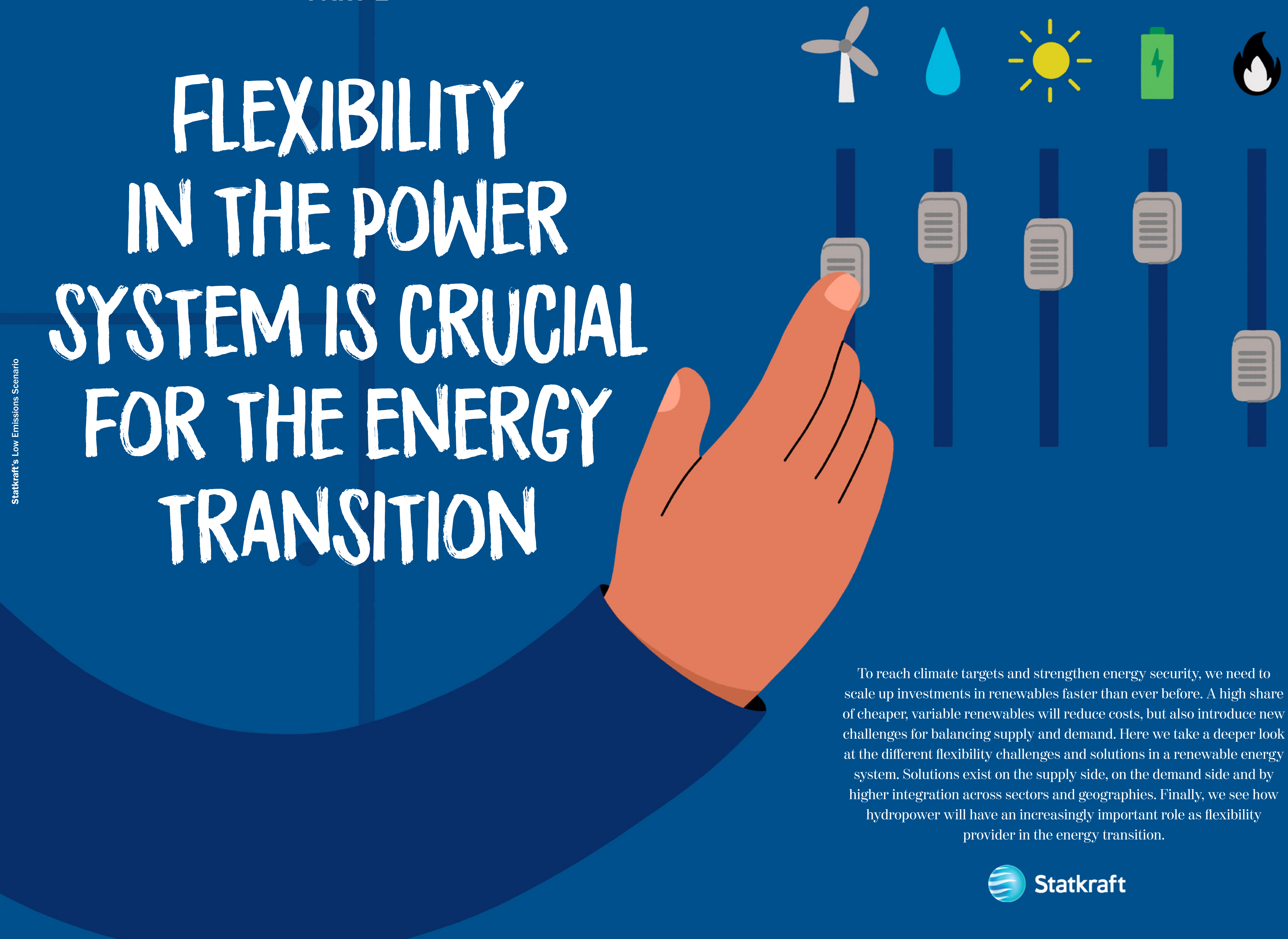
## Independence from Russian gas is ambitious but within reach

Overall, we find that it is feasible though challenging to reach the dual targets for EU to be fully independent from Russian gas by 2030, while reducing emissions by 55 per cent. This will require a rapid build-out of renewable capacity, with solar PV and onshore wind as the largest electricity generating technologies. Direct use of electricity in industry, buildings and transport is the most cost-optimal way to decarbonise end-use, together with energy efficiency, while renewable hydrogen production will need to be forced in through policies and support to reach the levels envisaged by EU.

Displacing industry fossil gas-use will be especially challenging and requires shifting some hydrogen from transport to industry, as well as increasing coal demand. In our analysis, the climate targets are still achieved as the increased coal demand is counterbalanced by more electricity and clean hydrogen in the end-use sectors and renewables in the power sector.

## PART 2

# FLEXIBILITY IN THE POWER SYSTEM IS CRUCIAL FOR THE ENERGY TRANSITION



To reach climate targets and strengthen energy security, we need to scale up investments in renewables faster than ever before. A high share of cheaper, variable renewables will reduce costs, but also introduce new challenges for balancing supply and demand. Here we take a deeper look at the different flexibility challenges and solutions in a renewable energy system. Solutions exist on the supply side, on the demand side and by higher integration across sectors and geographies. Finally, we see how hydropower will have an increasingly important role as flexibility provider in the energy transition.

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← In general, it is cost-optimal to expand both solar and wind power in regions with a high share of variable renewable power, as wind and solar resources often complement each other.

In the Low Emissions Scenario, the share of intermittent renewable power[i] will increase from around 10 per cent today to 65 per cent in 2050 globally. This is a global average; some regions will integrate an even higher share. Solar and wind power production will vary with weather and seasons. In addition, their marginal costs of producing electricity are low, which drives down electricity prices in windy and sunny hours.

As the share of intermittent renewables increase, so does the need for flexibility from other generation, transmission and distribution, and demand. Geography, resources, weather, supply mix, demand and interconnectors create regional variation in terms of flexibility needs.

The power systems today are quite flexible and can respond to variations in demand, unexpected outages of power plants and the existing variability of wind and solar PV production. However, with gradually higher share of solar PV and wind in the production mix and the closing of fossil plants, the need for flexibility in other parts of the system increase, extending from sub-seconds to several days or weeks.

In general, it is cost-optimal to expand both solar and wind power in regions with a high share of variable renewable power, as wind and solar resources often complement each other. This is especially true for larger regions with good interconnections. In general, interconnected power systems reduce the need for other flexibility solutions, as the larger system benefits from the differences in each power system and increases access to flexible solutions. For example, a power system with a high share of wind power and a power system with large hydropower reservoirs will function more optimally if they are connected through a common grid infrastructure, enabling the system to benefit from the differences between periods of high or low wind and high or low precipitation.

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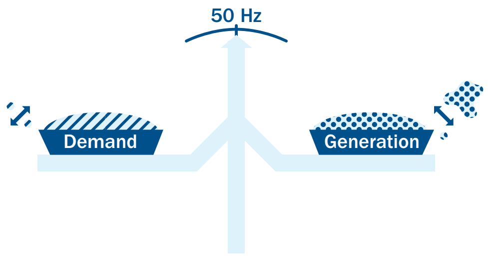
[i] Intermittent renewable power generation: The fluctuating nature or variability of solar and wind resources, which results in rapid changes in power production from solar PV and wind power.

## FLEXIBILITY SOLUTIONS CAN BE GROUPED INTO THREE CATEGORIES

| | |
|---|---|
| **System services - providing inertia, frequency and balancing for the grid**<br><br> <br>The balance of load and generation | To maintain the frequency and balance in the grid, *fast ramping* within seconds and *physical inertia* are necessary. Batteries can react immediately to imbalances in the system, so called fast frequency response. Many of the batteries built today are used for this purpose. However, this is not enough. Physical inertia is needed for momentaneous imbalance response to keep the power system stable. Historically, almost every power plant is run by a rotating turbine and can provide inertia, including hydro, but this is not the case with wind and solar. In the future other technologies, such as rotating grid stabilisers, are needed as well to provide grid stabilisation. |
| **Short-term intraday flexibility** | Countries with high share of variable solar and wind power will require more short-term flexibility within a day. Flexibility solutions that cover short time periods are expected to meet high competition. In addition to hydropower, batteries can provide flexibility for short periods of time of one or a few hours, and costs are expected to fall quickly in line with the steadily increasing number of batteries being produced. The electrification of transport is the main cost driver. Smart charging of electric cars will be an important source of short-term demand-side flexibility in the future as they stand still 95 per cent of the time on average. Therefore, smart EV charging, but also vehicle-to-grid, system batteries and other demand response, such as flexible green hydrogen production, will provide short-term flexibility. These solutions can exploit the future price differences during the day with higher share of solar PV in the power mix, thereby reducing the short-term volatility. |
| **Long-term flexibility covering days, weeks and months** | Long-term flexibility between weeks, months, and seasons is also increasingly important to be able to deal with conditions such as longer periods with no wind, higher winter demand, or differences in demand and supply between months and even years. There are fewer solutions to solve the long-term flexibility requirements. Upgrading and expanding the capacity of existing hydropower is one of the most economically attractive zero-emissions options to cover long-term flexibility needs in the power systems.<br>Countries without access to flexible hydropower must resort to other, more expensive zero-emissions solutions, such as hydrogen. If infrastructure and storage are built, hydrogen will be able to provide the same type of long-term flexibility as hydropower. This is a more expensive solution because of the cost of storage and the efficiency loss in producing power from hydrogen. Up to 70 per cent of the energy is lost when generating power from green hydrogen. The first 20-30 per cent of the energy is lost in the electrolyser when producing green hydrogen, and another 40 per cent is lost in power generation.[ii] Hydrogen for power generation is therefore only assumed to provide emission-free power in peak periods towards 2050, when lacking alternatives. The investment cost of hydrogen turbines is relatively modest compared to alternative solutions, which is key for peak-power technologies with limited running hours. |

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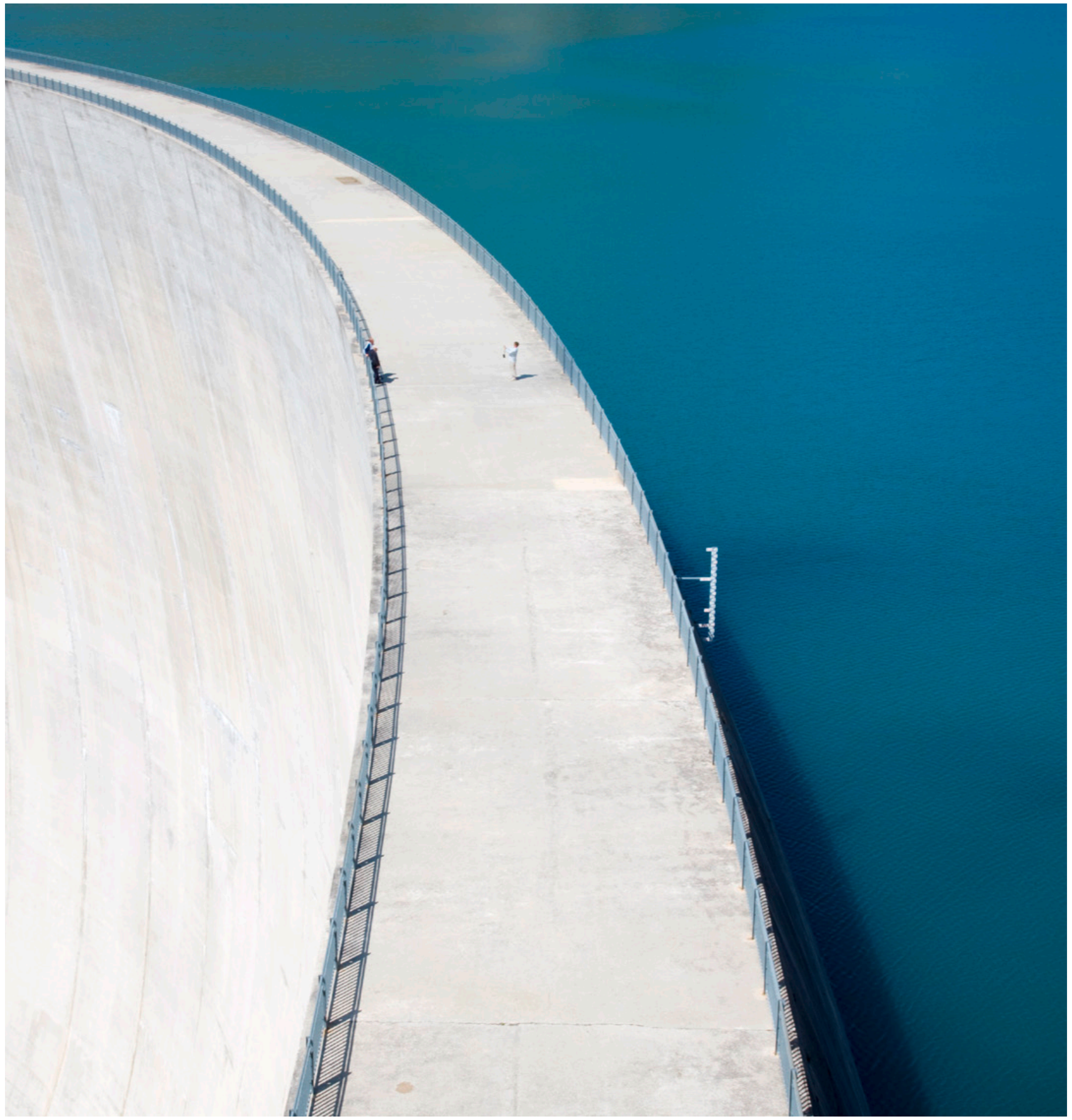
[ii] Using waste heat and utilising it in other sectors, such as district heating will reduce the energy loss in both processes.

DEEP DIVE

# Hydropower and flexibility



Hydropower is the largest renewable electricity provider globally and will continue to grow towards 2050. The storage potential from hydropower reservoirs covers 99.9 per cent of global electricity storage today. While battery storage covers only 0.05 per cent with more than 90 per cent located in electric vehicles. Rapid growth of renewable power is needed to reach the climate and energy security targets. Hydropower will be vital going forward, with its unique ability to provide energy security and system stability, even in regions with a low hydropower share in their electricity mix.

Hydropower is the largest provider of renewable electricity globally and generates nearly 80 per cent more electricity than solar and wind power combined. Even so, this is just a quarter of the electricity generated by fossil fuels today. Therefore all renewable technologies are essential to phase out fossil fuels in the power sector, with hydro being a vital piece to secure system balance.

Providing flexibility is a unique quality for hydropower compared to other renewable technologies. Even in regions with a low share of hydro in the electricity mix, hydropower can still be a large contributor to the energy security and system stability in the region. Today, hydropower exists in 160 countries. There are large geographical differences, and ten countries are responsible for more than 70 per cent of global hydropower generation as there are limitations in terms of locations with suitable river systems and height differences (Figure 25).[62]

There is still significant growth potential for hydro globally. The techno-economic potential indicates that capacity could (in theory) grow two to five times from today's levels, but this is before taking other environmental considerations into account.[i,63]

In 2021, global hydropower capacity increased by around 30 GW, mainly driven by growth in Asia. In the Low Emissions Scenario, hydropower will continue to grow from around 1,360 GW today and will surpass 2,000 GW in capacity and 7,000 TWh in production globally by 2050 (Figure 26), becoming the fourth largest electricity generating technology globally after solar PV, onshore and offshore wind.

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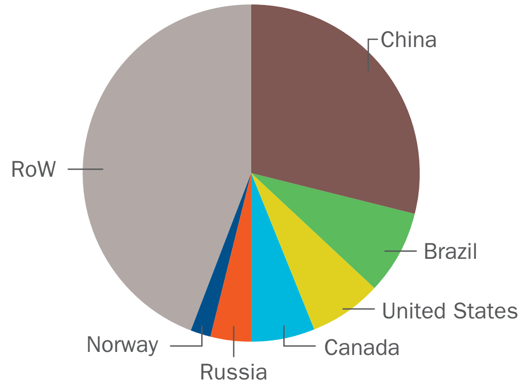
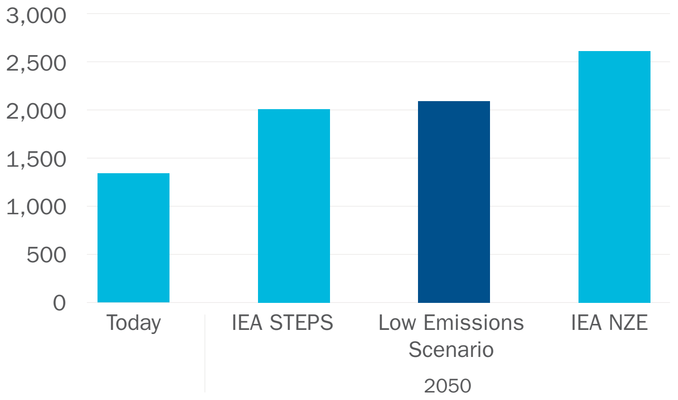
[i] Thorough site-specific feasibility studies are required to obtain the techno-economical potential for hydropower, and with that in mind, the potential is estimated to be around two to five times today's hydropower production. Most of the potential is in Asia and Africa which will see high power demand growth and only a share of the potential is realistically feasible for environmental and other considerations.

25 Global hydropower capacity by country (top five plus Norway and Rest of the World (RoW))[64]



26 Global hydropower capacity (GW) today and in 2050 in Low Emissions Scenario compared to IEA[65]

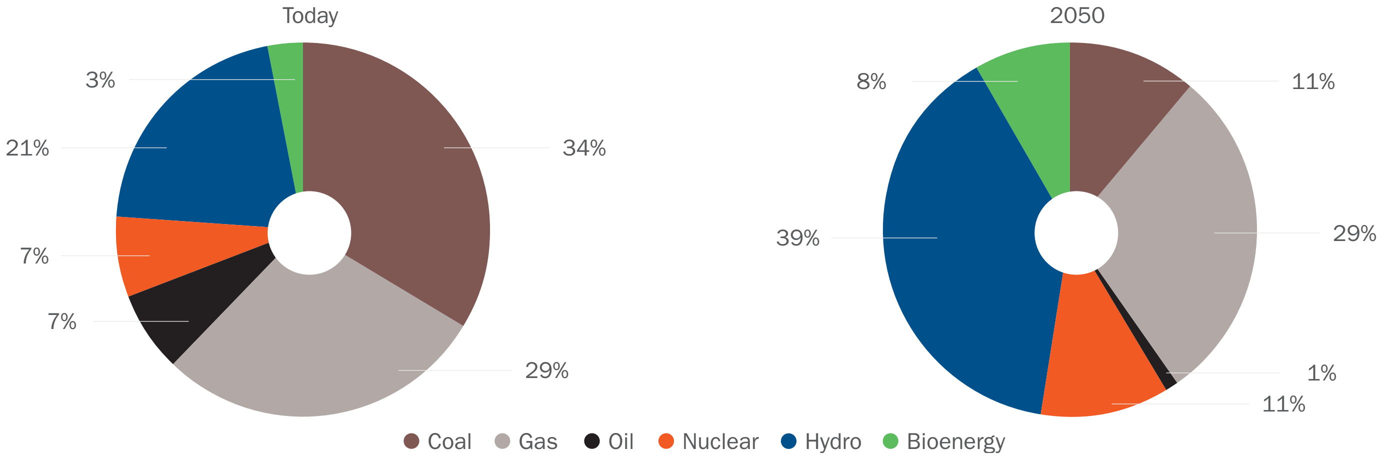


27 Key characteristics of flexible solutions across the time dimension[67]

Flexibility for power ←→ Flexibility for energy

| | System services | | | | Intraday (short-term) | Long-term | |
|---|---|---|---|---|---|---|---|
| | Sub-seconds (fast frequency response) | Sub-seconds (system, inertia) | Seconds | Minutes | Hours | Days, weeks | Months (seasonal arbitrage) |
| **Reservoir hydro** | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Run-of-river** | | ✓ | | | | | |
| **Pumped hydro** | | ✓ | ✓ | ✓ | ✓ | ✓ | |
| **Battery** | ✓ | | ✓ | ✓ | ✓ | | |
| **Gas/coal power** | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Demand response (incl. electrolyser and smart charging)** | | | ✓ | ✓ | ✓ | ✓ | |
| **Hydrogen-to-power (H2P)** | | | | | | ✓ | ✓ |

28 Global flexible production capacity, share per power supply source today and in 2050[68] (%)



## Hydropower provides increasingly valuable flexibility to the global power system

Hydropower can provide carbon-free electricity production, combined with flexibility and security of supply due to the following key properties:

**Renewable energy** – gross energy generated and delivered to the power system

**Flexibility** – energy when needed: the ability to move electricity generation in time by storing (and possibly pumping) water and thereby delivering energy to the system when needed. Reservoir and installed capacity are key factors.

**System services** – to stabilise the grid: the ability to deliver inertia, reactive power or other system services within seconds and minutes to maintain the necessary grid frequency.[i,66]

Hydropower is the only renewable solution today that can provide flexibility within a range from seconds to days, as well as store energy for weeks, months or years (Figure 27). Due to the phase-out of dispatchable coal and nuclear, hydro will have an increasingly important role as a flexibility provider going forward, almost doubling its share of global flexible capacity towards 2050, surpassing both coal and gas power (Figure 28).

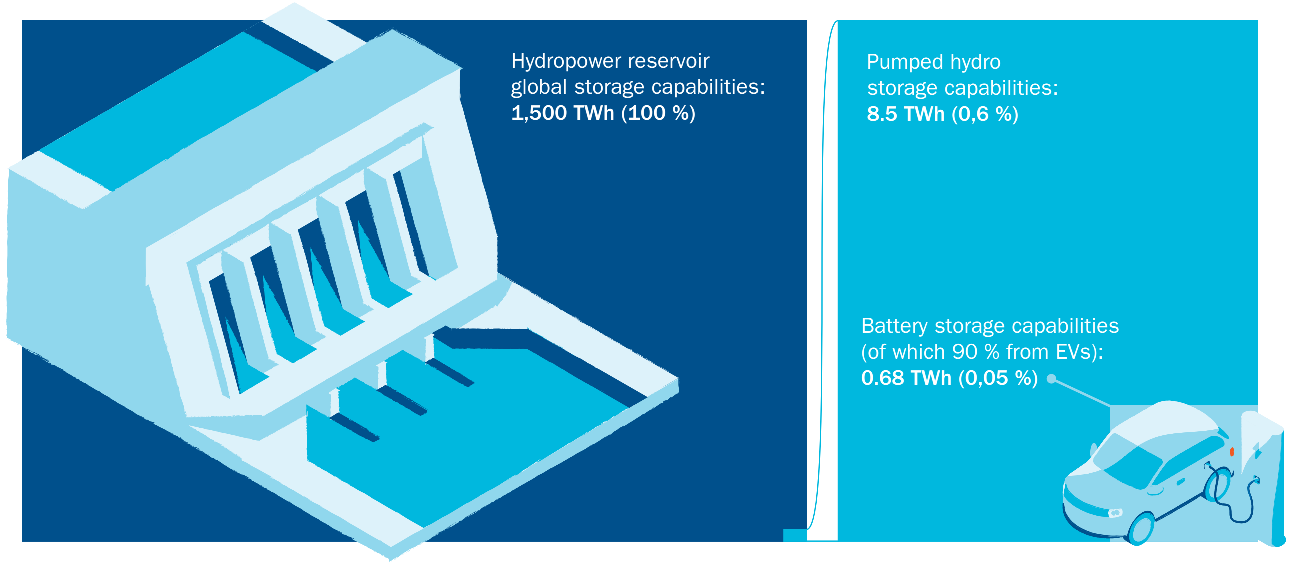
The energy storage potential from existing hydropower reservoirs globally is unique, covering more than 1,500 TWh of energy. This covers 99.9 per cent of global electricity storage today. The energy can be stored and discharged at a moment's notice depending on the power system needs and the size of the reservoir. In comparison, battery storage has grown exponentially the last years, but it still only covers 0.05 per cent of global hydropower reservoir storage potential (Figure 29).[69] On top of this, more than 90 per cent of the battery storage capacity globally sits in electric vehicles. This makes smart charging key to unlock the flexibility potential for the power system from batteries.[70] The value from energy storage and flexibility of hydropower plants will increase in a future power system with more intermittent power.

Hydropower facilities have an average lifespan of 50 to 100 years. In many mature markets, most of the hydropower potential is already built and the global fleet is ageing. More than 50 per cent of the hydropower fleet is more than 40 years old and needs larger upgrades. Even younger hydropower plants may need large upgrades if they have been lacking the necessary maintenance to run optimally.[72] Here, upgrades and extensions of existing plants can add valuable flexibility to the power system. Existing hydropower plants can be redesigned by increasing installed capacity, increasing waterways and storage capacity, installing new turbines, and digitalisations. Together, this will increase flexibility with faster ramp-up and ramp-down, as well as providing additional energy. Increasing the installed capacity will typically enable the plants to run more flexibly by shifting production to periods with low wind or no sun or high demand, while the absolute annual electricity production remains essentially the same if the storage capacity and waterways are not altered.

Upgrading and expanding the capacity of existing hydropower is one of the most economically attractive options for covering long-term flexibility needs in a decarbonised power system.

Hydro is increasingly important for stabilising the grid due to its ability to provide inertia and quickly change production at relatively low start and stop costs. But even hydropower is not flexible enough in all situations. Today hydropower contributes to frequency control through reserve markets regulated by the transmission system operators (TSOs) to ensure that the frequency in the power system does not deviate more than the allowed limits.[ii,73] However, most hydropower turbines should not run below 60 per cent of production capacity as this may damage the turbines. Therefore, current research focuses on utilising the plant's full storage and power capabilities by designing turbines and associated systems that can withstand faster ramping rates and more frequent starts and stops. It is the response time that prevents hydropower from offering the same flexibility services as system batteries today, but with new or improved turbines it will be possible to run hydropower plants at lower loads and increase the reaction time.[iii,74]

29 Global storage capabilities for hydropower with reservoir, pumped hydro, and batteries today[71] (IEA, Statkraft)



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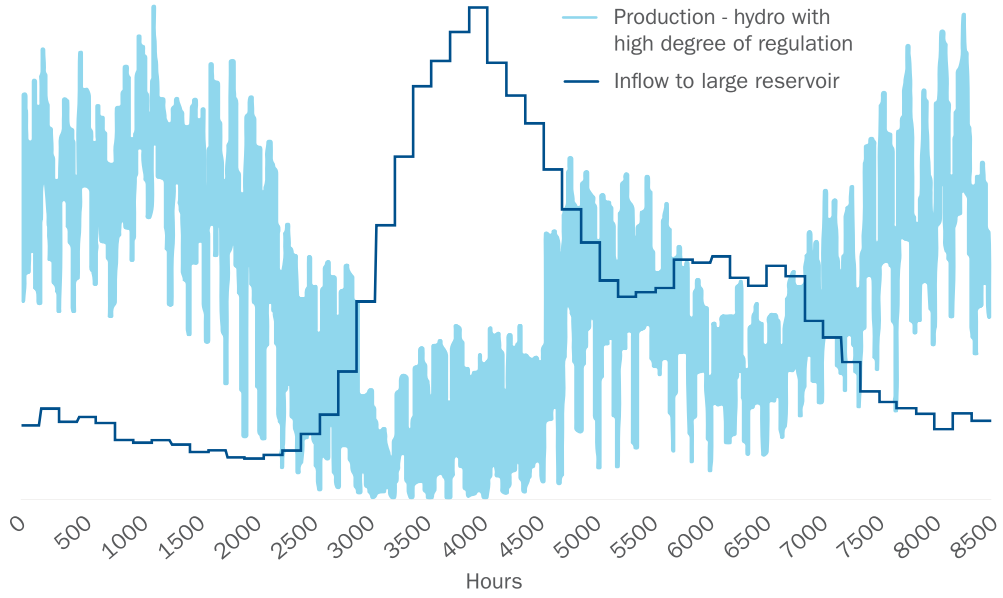
[i] Energy: Energy and power are closely related. Energy is the ability to cause change such as mechanical motion of a turbine (joule or kWh)[73]

[ii] Reserve services to the grid operator differ based on their response time, from within one second to up to 15 minutes (Fast Frequency Reserves (FFR), Frequency Containment Reserves (FCR), automatic Frequency Restoration Reserves (aFRR) and manual Frequency Restoration Reserves (mFRR)). Hydropower provides all reserve services today except the fast frequency response within 1 second.

[iii] Tighter restrictions on variations in water levels in reservoirs, specific requirements to ecological flow in the river or minimum discharge through the power plant may have significant impact on a plant's ability to supply flexibility and system services and such overall system impact needs to be carefully assessed with a holistic approach. Studies have found that there is little correlation between energy production and contribution of balancing and flexibility services.[73] Thus, loss of energy production alone is not a good measure for evaluating the impact of changing regulations.

**30** Hydropower with long term storage in large reservoir will save inflow in the reservoir in periods with low prices and demand, and produce when prices and demand are higher, being able to optimise dispatch according to demand and prices (GW per hour in one year, illustration). (Statkraft analysis)

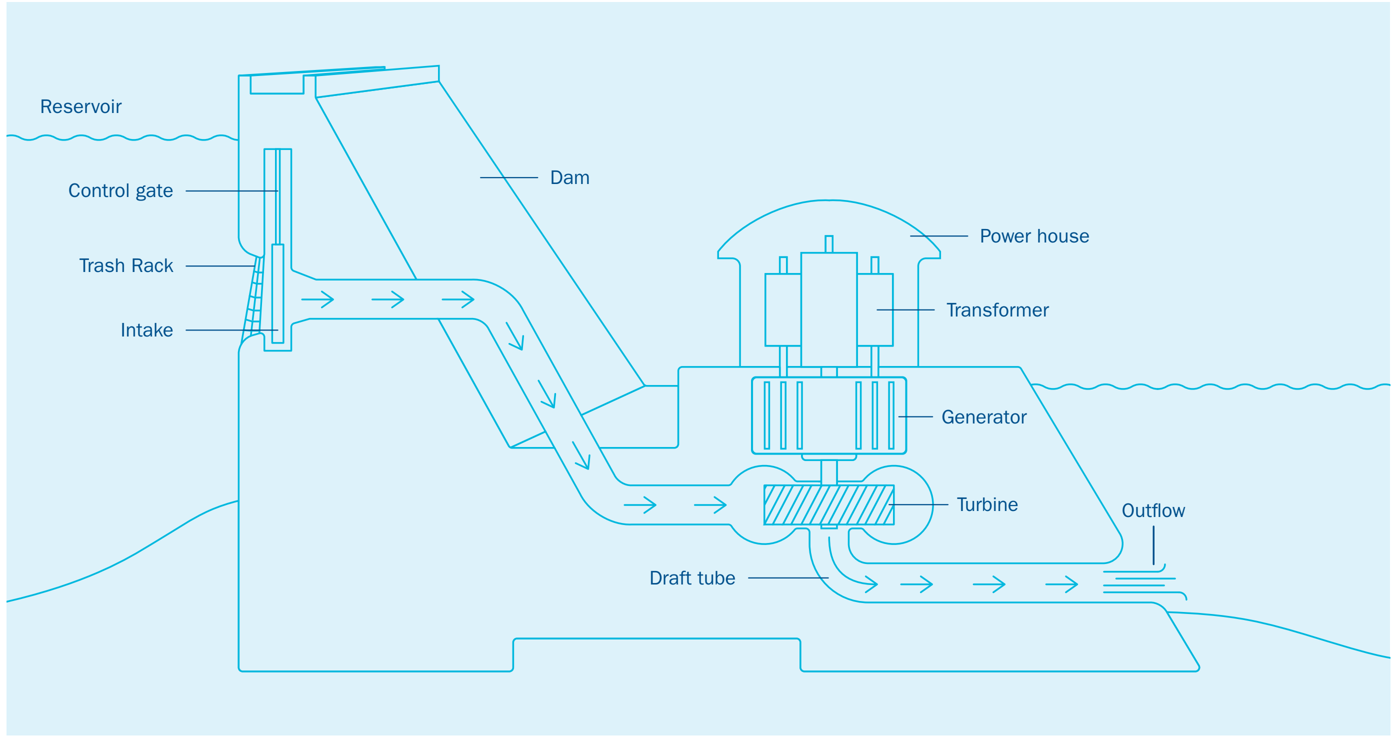


- Hydro with long term storage will save inflow in the reservoir in periods with low prices, and produce when prices are higher.
- Less flexible hydro will follow the inflow pattern and be much less able to optimize dispatch according to prices.
- Hydro is the main source of flexibility in the Nordic system and will benefit form increase in both short and long term flexibility needs.

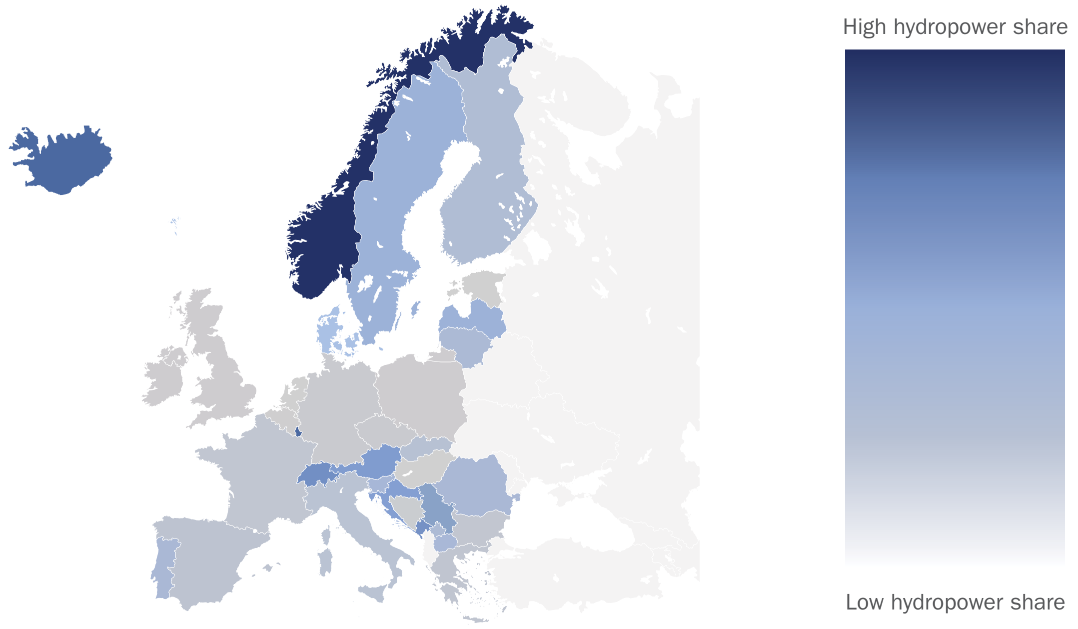
### FLEXIBILITY CHARACTERISTICS VARY DEPENDING ON TYPE AND DESIGN OF THE HYDROPOWER PLANT

Hydropower uses the energy from falling water or the flow of a river to generate electricity. The greater the height difference between the water intake and the turbine, the more energy stored in the water. Hydropower plants come in many different sizes[i,75]. Each plant is unique and therefore the flexibility services and the ability to move production in time vary, depending on turbine type, plant design, reservoir size, location, etc. Each power plant is regulated differently and the value they provide to the grid and the overall power system is not necessarily linked to their production levels. Flexible hydropower can be key for handling local and regional grid challenges and to ensure local grid stability.[76]

↓ **Hydropower plant with reservoir**



**31** Share of hydropower in European power mix by country[78]



The three main categories of hydropower provide different types of flexibility:

**Run-of-river plants** – hydropower plant placed in rivers, fitted to a large water flow, as the water pressure from the height difference is low.

**Plants with reservoir** – hydropower plants that get water from a higher water source such as a lake with a dam – also known as a reservoir. It requires waterways and pipes to lead the water to the power plant.

**Pumped storage plants** – a hydropower plant with a reservoir that has the ability to pump water back up into the reservoir thus being able to generate electricity when the demand is high, and pump back and store electricity when the demand and price is low.

Run-of-river is the least flexible of the three, but it is still important for the system as it provides inertia and creates stable production following the river flow. Hydropower plants with a reservoir and pumped hydropower can generate electricity, act as storage, and provide both capacity and flexibility. Their contribution to flexibility is also dependent on seasonal water availability and may result in large annual variations. The storage duration of plants with a reservoir typically ranges from a few hours to weeks to even months. Pumped hydro can, in addition, serve as a demand-side flexibility resource when in pumping mode.

## Hydropower's role in the Nordic and European power system

In Europe, the recent REPowerEU plan has accelerated the already strong trend of shifting to a renewable power system that is dominated by solar and wind (see deep dive: REPower EU). This leads to the increased importance of remaining dispatchable generation, including hydropower. All European countries have some hydropower in their power mix, however there are large differences. Hydropower is especially common in the Nordic and Alpine countries (Figure 31), and cross-border interconnectors can provide much needed flexibility to the rest of Europe.[77] A power system such as in the Nordics, Austria, Switzerland, and Albania, all based on flexible hydropower, has a unique ability to handle large variations in other renewable power sources and keep price fluctuations lower over time. Hydropower is also weather dependent, and the variation in precipitation from year-to-year results in high variability in generation. Storage in reservoirs helps reduce this variability over time.However, in hydro-dependent regions, several consecutive dry years increases the need for import, while if there are several wet years to follow, most hydro-dependent countries, such as Switzerland, Norway, and Austria, will produce more electricity than they need, which can be exported to neighbouring regions.

In general, combining and connecting the distinctive strengths and characteristics of different technologies across geographies enable a more robust power system. For example, hydropower can complement solar PV and wind power by providing flexibility, storage, and energy during times of low solar and wind generation, while the water can be stored in sunny and windy periods. This increases the robustness of a decarbonised power system. To ensure that the power system is always in balance and has the right quality of delivery, a future electricity market should ensure the right price signals for the different elements of what the system needs (i.e., energy, flexibility, and system services).

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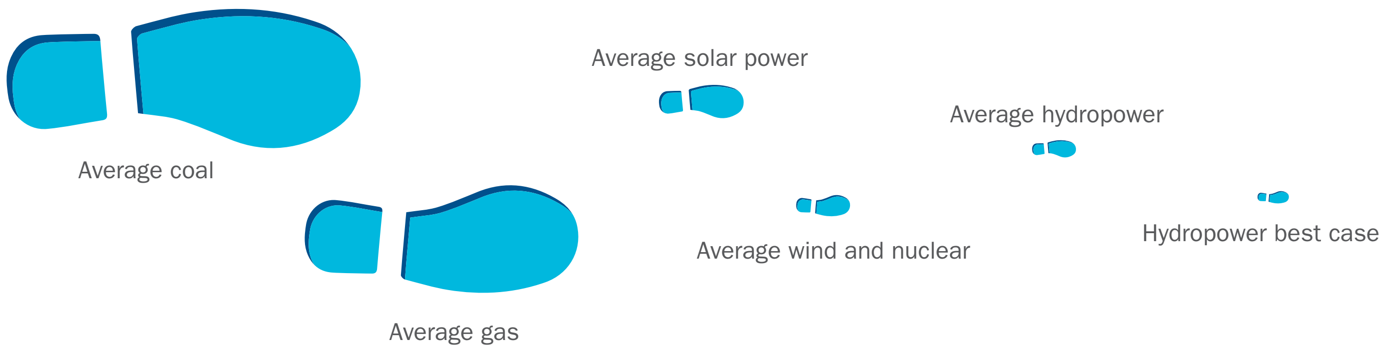
[i] Large scale (>10 MW for example Tokke power plant (430 MW), small scale (1 – 10 MW, for example Nedre Bersåvatn power plant (4 MW)), mini (0.1 - 1 MW like Mofjell power plant (0.6 MW)) and micro (< 0.1 MW).[75]

**32** Average carbon footprint for different power plants (size corresponding to kg CO$_2$e/kWh)[80]



## Hydropower in the broader sustainability context: carbon footprint and flood control

Hydropower's ability to regulate rivers and lakes can increase flood control, and its flexible operation is an enabler to integrate more intermittent renewables and secure stability in the power system.

Renewable hydropower has a low carbon footprint, much lower than fossil power plants, even with carbon capture, and on par or lower than wind and solar when looking at its complete life-cycle impacts.[i] Global average for hydropower lifetime emissions is around 18.5 gCO$_2$ per kWh generated, but as emissions are much more site- and project-specific than other technologies, many hydropower plants have even lower emission levels (closer to 6 - 11 gCO2 per kWh).[ii,79]

Higher lifetime emissions can be due to longer than average transportation distance for building materials, as this in combination with emissions from steel production can cover a major portion of the emissions.[81] In tropical regions, methane emissions from hydropower reservoirs may also account for a significant amount of the emissions.[82]

With global warming and increasing temperatures, precipitation patterns are changing, and in some regions, we experience altered inflows and an increased risk of floods.[83] In general, floods will increase in frequency as well as magnitude and spread to more regions.
Even if global warming is limited to 1.5 degrees, heavy precipitation over land will increase. IPCC states that each 10-year event for heavy precipitation over land is expected to happen 1.5 times more frequently, and will be 10 per cent wetter, while in a 2-degrees scenario, this can happen twice as often.[iii,84]

Hydropower has an increasingly important role in preventing damages and loss of life from flooding. Hydropowerwith reservoirs can deliver important flood control measures, as the flow of water can be managed and optimised to help reduce the floods downstream. The plant operators can collect and manage floodwater in the reservoir and control the flow of water past the hydro plant to the waterways below, thereby preventing rushes of water, and potentially saving lives and properties.[85]

Hydropower represents a critical part of power systems around the world and must be seen in connection with alternative uses of water (e.g., canals, irrigation, recreational, flood risks). Because of the sensitivity of ecosystems and habitats, water flow and water levels are often regulated and have an upper and lower limit in the lake or reservoir or in the river. It is important to find the right balance between minimising environmental impact while maximising the value hydropower delivers in the form of renewable electricity, flexibility, climate mitigation, energy security and flood reduction capabilities for the region, as well as for the total energy system.

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[i] When talking about a power plant's life cycle, emissions from every stage of the power plant's life is taken into account (i.e., emissions from fuel extraction, building materials, construction, power production, etc.).
[ii] The carbon footprint varies between projects, several hydro plants are in the range 10-100 gCO$_2$/kWh, and some even higher
[iii] Compared to the reference period 1850 to 1900

← As an illustration, during the flood in Norway in October 2014, Flåm and Odda recorded damages for over EUR 50 million, but there were no reported damages in the regulated watercourses in neighbouring Aurland and Tyssedal.

→ Three Gorges Dam in China can hold a water level of up to 175 metres but regulates the water below 165 metres to protect against possible flooding. In 2021, the dam restricted water discharge at 19,000 cubic metres per second, more than half the speed of the average inflow into the reservoir (of 40,000 cubic meters).

# Renewable hydrogen is needed to reach climate targets while providing valuable flexibility

In the Low Emissions Scenario, renewable hydrogen production will play a significant role in the energy systems globally and be a major source of flexible power consumption. In recent years, there has been tremendous development in policies, projects, and the global hydrogen industry. In the Low Emissions Scenario, hydrogen demand will increase to three times today's consumption in 2050, and will become 100 per cent emission-free, gradually replacing all the world's existing fossil hydrogen demand (Figure 33).

The power needed to produce renewable hydrogen[i] results in around ten per cent of the total increase in global power demand by 2050, but there are large regional differences. The increase is possible due to the flexibility in hydrogen production when connected to grid and storage solutions.

As demand for hydrogen does not always match periods with abundant sun and wind and lower power prices, hydrogen needs to be stored to benefit from power price variation and maintain low production costs.[ii] Seasonal storage can be beneficial in markets with significant power price differences between seasons, for example in Northwestern Europe. Storage in salt caverns, is expected to be the cheapest way to store large volumes over longer periods, where available. Storage in compressed tanks is beneficial for optimising production over a few hours and days. In regions with high share of solar PV in the mix, such as in Chile, the price difference during the day is expected to incentivise flexible hydrogen production during daytime combined with short-term storage.

In the near term, due to lack of dedicated hydrogen infrastructure, production is expected to be in proximity to industry or transport demand. In the longer term, hydrogen transport infrastructure is expected to be gradually built out. For small volumes and short distances, the most cost-efficient way to transport hydrogen is considered to be in compressed or liquid form via trucks. For larger volumes and medium distances, repurposed fossil gas pipelines will be the preferred option. In Europe, existing fossil gas pipelines have the potential to be converted to hydrogen pipelines, creating an interconnected, regional European hydrogen market. For long-distance intercontinental transport, converting to ammonia and transporting via ships seems more promising. However, as converting hydrogen to renewable ammonia and cracking back to hydrogen adds significant costs, pipeline transport is expected to be the least costly and preferred option within a region. The future for global hydrogen trade across continents is more uncertain and is expected to be mainly in the form of a final product, such as green ammonia or green steel.

An alternative to green hydrogen is to produce hydrogen from fossil fuels with carbon capture and storage (CCS) – blue hydrogen. This process still emits around five to 10 per cent $CO_2$. Even though green and blue hydrogen production, in general, are expected to complement each other, the current high gas prices have added uncertainty to the blue hydrogen outlook. CCS already has high up-front investment costs. Blue hydrogen looks more competitive in parts of the world that have abundant cheap fossil gas resources and suitable areas for storing $CO_2$, such as in the US and Qatar.

The competitiveness of green hydrogen will gradually improve relative to both blue and grey hydrogen. However, the actual timing for when cost parity is reached for green hydrogen compared to the alternative fuels will vary for each application and geography.

The importance of grid-connected, renewable hydrogen for the power systems increases steadily up to 2050, and as electrolyser costs fall, power prices will gradually have more impact on hydrogen costs (Figure 34). Electrolysers will be able to provide valuable flexibility to the system, from minutes to hours and days.

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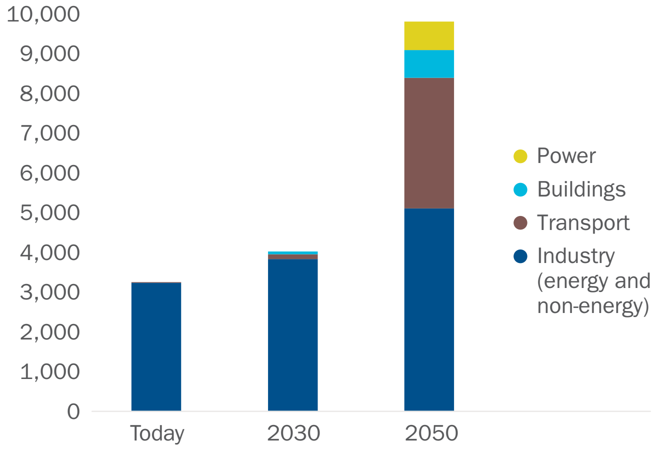
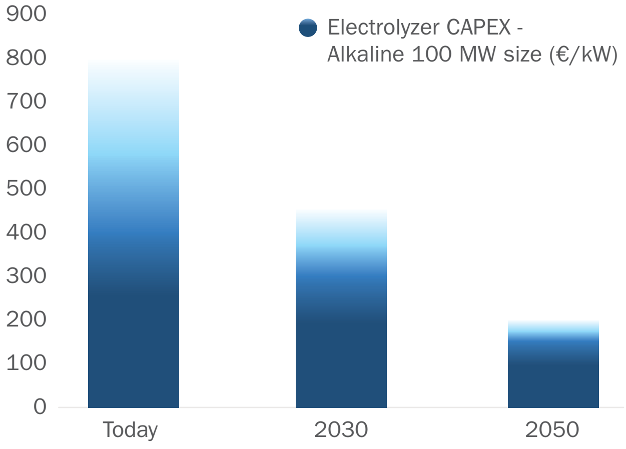
[i] Renewable (or "green") hydrogen is produced from renewable power in electrolyser and is emission- free. "Blue" hydrogen is produced from fossil gas with CCS and is 90-95% emission-free while "grey" hydrogen is produced from fossil gas without CCS and emits 9.9 tCO2/tH2.[86] "Grey" hydrogen is predominantly produced from fossil gas through steam-methane-reforming (SMR), and it is primarily used in refineries to remove sulphur from fuels and in production of ammonia today, responsible for around 2% of global greenhouse gas emissions.

[ii] Flexible hydrogen production also reduces the number of hours in which the power plant needs to shut down variable power production to balance the grid (curtailment).

**33** Global demand for hydrogen by sector (TWh)



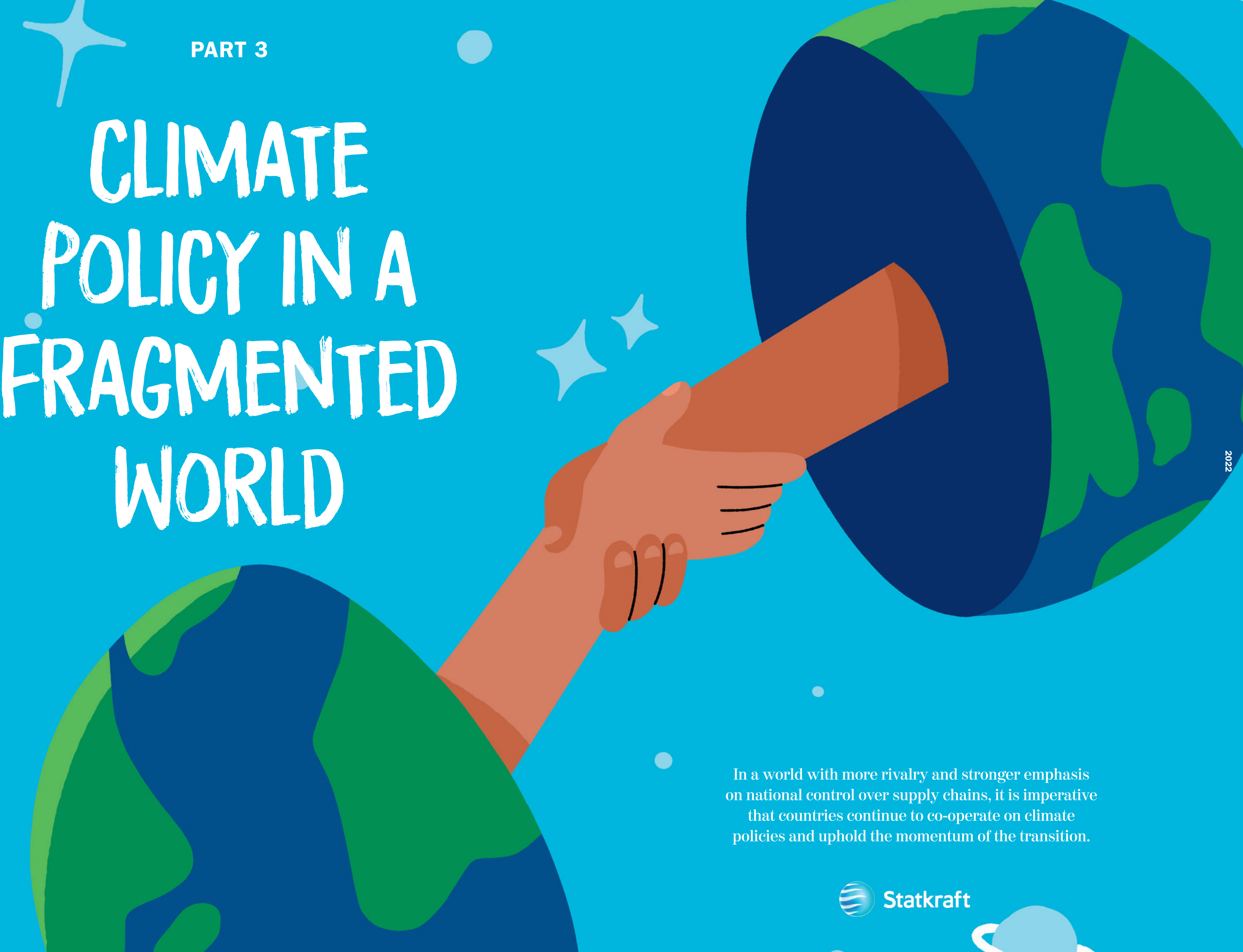
**34** Electrolyzer Capex from today to 2050



↑ **Storage in compressed tanks is beneficial for optimising production over a few hours and days. In regions with high share of solar PV in the mix, such as in Chile, the price difference during the day is expected to incentivise flexible hydrogen production during daytime combined with short-term storage.**

PART 3

# CLIMATE POLICY IN A FRAGMENTED WORLD



In a world with more rivalry and stronger emphasis on national control over supply chains, it is imperative that countries continue to co-operate on climate policies and uphold the momentum of the transition.

Statkraft

← **The global climate agenda has recently been overshadowed by the war in Ukraine and COVID-19 pandemic recovery. The level of uncertainty surrounding energy markets has increased**

## Countries are committing to net zero while risk of a disorderly transition has increased

In November 2021, the annual UN Climate Change Conference (COP 26) concluded on the Paris Agreement Rulebook and agreed on the Glasgow Pact. The latter included a strengthening of national targets within one year and the phase-down of coal.[88] Many countries communicated sharpened targets ahead of or during the COP26 meeting, most notably India with a 2070 net zero target. Now, more than 80 per cent of global emissions are covered by net zero announcements or pledges (Figure 35). However, current ambitions are not enough. Research shows that implementing policies from end-2020 would lead to 3.2 °C of warming, implementing current targets would lead to 2.4-2.7 °C of warming, and a full implementation, including all announced net-zero ambitions, could keep global warming at 1.8-1.9 °C. The fact that countries are willing to commit to this level of ambition gives reason for hope.[89]

Still, the global climate agenda has recently been overshadowed by the war in Ukraine and COVID-19 pandemic recovery. The level of uncertainty surrounding energy markets has increased, and energy self-sufficiency is now at the top of the policy agenda. The world is more fragmented which could make it more difficult to coordinate the global response to climate change and build trust. Global and regional co-operation that leads to accelerated and strengthened government action is vital if we want to solve the climate crisis.

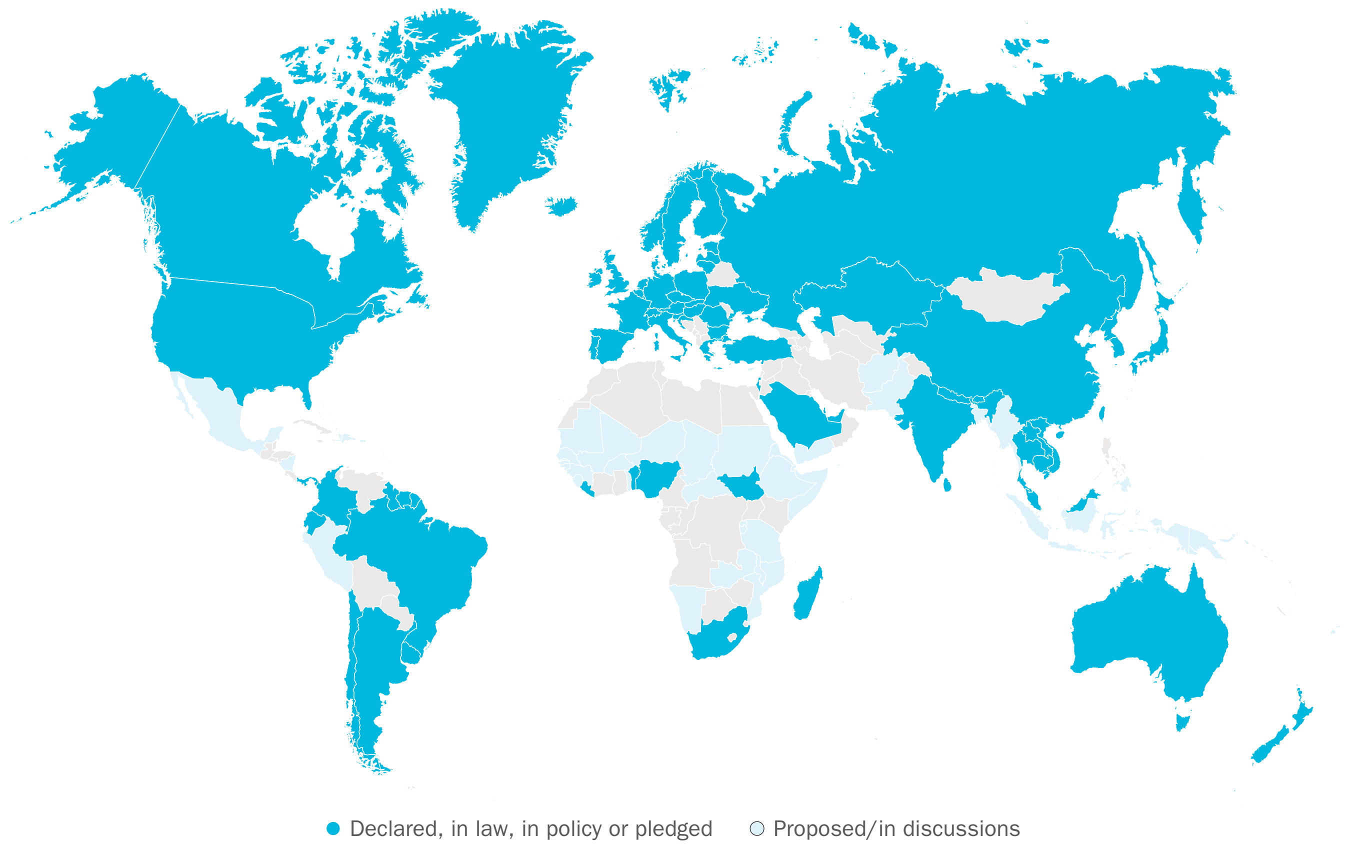
A more intense rivalry could make it harder to get the world's largest economies to commit to more stringent climate targets and retain the trust in commitments to reach the targets. It could also decrease pressure on laggard countries, as other considerations may trump climate change in importance for global diplomacy. So far, climate change has been one of few areas where China and the US have been able to co-operate and move forward.

In the Low Emissions Scenario, more regional supply chains are expected to emerge with the increased geopolitical tension, while the global momentum towards solving the climate crisis is preserved despite global tension in other fields.

Affordability is much discussed in the green transition – but this is now being challenged by everything becoming more expensive in the last year. The energy crisis has hit import-dependent developing countries especially hard, already heavily indebted on the back of the COVID-19 pandemic. This has reduced the governments' ability to fund renewable energy projects. Also, the high cost of capital and borrowing costs are making capital-intensive technologies less attractive. The developing world accounts for one-fifth of clean energy investments, but two-thirds of the global population. Insufficient financing of clean technologies in emerging economies contributes to the risk of a disorderly transition.

Ahead of COP27 in Sharm El-Sheikh in Egypt, the focus has been on a just transition.[90] This includes how the most vulnerable countries and communities, in terms of dealing with the consequences of global warming, could be financed. Developed countries were encouraged to deliver on the financing commitments they have made, as well as raise their pre-2030 ambition, for developing countries to receive the technical and financial support needed to solve the climate crisis on a global level.

**35** Countries and nations with ambitions of net zero emissions[87]



## Carbon price is one of the most efficient ways to reach climate targets

Strong climate ambitions must be followed up by concrete and immediate actions and measures to reach targets and goals. Putting a price on carbon is one of the most efficient policy measures to reduce emissions. For countries with a dual goal of reduced emissions and reduced imports of fossil fuels, carbon pricing as a policy tool supports the achievement of both.

The Paris Agreement Rulebook Article 6 on carbon markets and co-operation was agreed upon at COP26 last year. This sets out guidelines that enable countries to co-operate (to reduce emissions) by exchanging carbon credits at country-level or project-level in a transparent and accountable way. Agreeing on clear international rules for carbon markets is an important step to help countries to go further than they would do without co-operation, while avoiding double-counting.

## Carbon contract for difference reduces investment risk in clean technologies

While carbon pricing is advantageous when moving from fossil to clean technologies, investment in innovative low carbon technologies is not without risk, including high upfront costs. Carbon prices do not always reflect the true social cost of carbon in the economy, and future price levels are often uncertain and volatile. In most regions, carbon pricing is one of several policy tools applied to reach climate targets. To accelerate investments in clean technologies, carbon pricing coupled with carbon contracts for difference schemes can help enhance predictability and reduce investment risks. This is a government support mechanism than can cover the gap between actual costs of clean technologies and the carbon price levels. This can be a powerful tool in developing less mature technologies and help mitigate the first mover disadvantage for technologies such as clean hydrogen for transport.

## Avoiding carbon leakage between markets is important

Currently, the world is following regionally diverging emission pathways. As such, the countries and regions in the lead, such as EU, risk carbon leakage to other countries with weaker climate ambitions. To minimise the risk of carbon leakage and to push other countries to increase their own ambitions, a Carbon Border Adjustment Mechanism (CBAM) for key sectors is

← The energy crisis has boosted global energy investment to an expected record USD 2.4 trillion in 2022, according to IEA, an eight per cent rise compared to 2021. Almost 60 percent of this is in clean energy.

proposed by the European Commission. The intention is to add a price on imports that more accurately reflects their carbon content. Similar carbon costs for products imported as for products produced within EU can be achieved by indexing the carbon import price level to the actual carbon price in the EU (EU ETS). In a transition period, such a mechanism, if designed and implemented in a good way, could help regions converge towards a more aligned and ambitious emissions pathway.

## Investments in clean technologies are increasing – but much more is needed

The energy crisis has boosted global energy investment to an expected record USD 2.4 trillion in 2022, according to IEA, an eight per cent rise compared to 2021. Almost 60 percent of this is in clean energy. The lion's share of the investment is in renewable power, electrification of mobility, and improved efficiency, driven by higher energy prices. There is also momentum in new and emerging technologies, with huge growth in battery energy storage and clean hydrogen, the latter boosted by Russia's invasion of Ukraine and EU targets for hydrogen. However, the annual investments are not sufficient to limit global warming to 1.5 °C, and not enough to reach the announced climate targets.[91] To direct future investments towards clean and sustainable projects, the EU has created a common classification system for "sustainable economic activities". The EU taxonomy provides a ecommon language and clear definitions of sustainable investments. This could be a powerful tool to switch capital from fossil to clean and sustainable technologies going forward.[92]

Redirecting capital to clean technologies investments with the speed required represents a major coordination challenge that can only be solved by a clear commitment to climate targets backed up by both long-term and short-term policies.

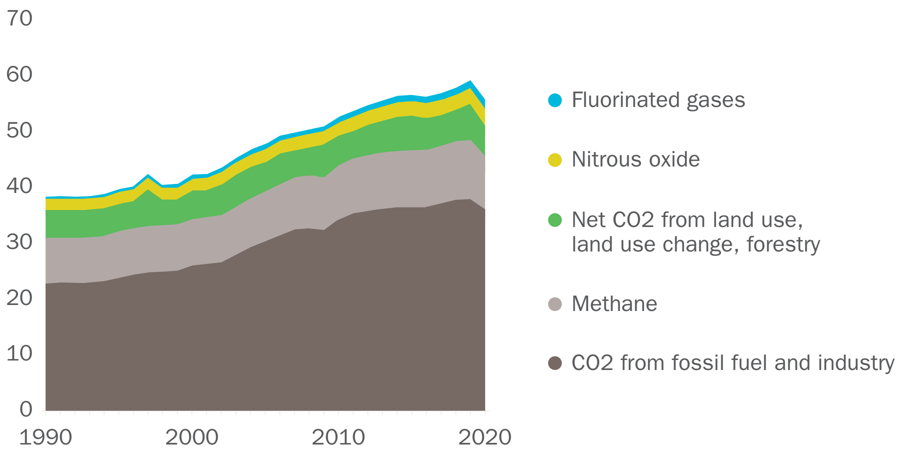
In this regard, the passing of the "Inflation Reduction Act (IRA)" by the U.S. Congress is a positive sign that the United States is committed to reaching its goals under the Paris Agreement. The package includes USD 386 billion in energy and climate spending, including tax credits for green electricity, manufacturing, energy efficiency and clean fuel and vehicles. IRA is estimated to reduce U.S emission by 40 per cent by 2030 (as compared to 2005 levels), a significant step up from the previous reduction estimates of 24 to 35 per cent per the previous policies.[93,94]

The EU taxonomy could be a powerful tool to redirect capital from fossil to clean and sustainable technologies.

## DEEP DIVE

# The Low Emissions Scenario in an IPCC context

**36** Global net anthropogenic GHG emissions ($GtCO_2$-eq) 1990–2020[98]



To stay within a 1.5°C warming, we need to reduce greenhouse gas emissions by 43 per cent within the next eight years. This is extremely challenging. Here we compare the Low Emissions Scenario with the latest IPCC climate scenarios in line with 1.5°C and 2°C warming. In the Low Emissions Scenario, energy-related $CO_2$-emissions drop by 60 per cent from today to 2050. This is significant, but still not enough for a 1.5°C pathway. More renewables and a higher share of electricity in final energy are needed to be in line with the 1.5°C scenarios, while hydrogen is on par with the Low Emissions Scenario. In addition, the use of carbon dioxide removal solutions is required to get rid of the last and most expensive $CO_2$ molecules.

In April 2022 the Intergovernmental Panel on Climate Change (IPCC)[95] published its third and last main report in the sixth assessment cycle of the state of knowledge related to climate change (AR6).[i] Since the last assessment report was published in 2014, it has become even clearer that human activities have warmed the atmosphere, ocean, and land. The IPCC report concludes that the world has already become 1.1°C warmer and every additional tenth of a degree of increased temperature will have a large negative effect.[96]

### GREENHOUSE GAS EMISSIONS ARE RISING, BUT AT A SLOWER PACE

As clearly stated in the third report of AR6, we are not on track to limit global warming to 1.5°C. The total net anthropogenic[ii] greenhouse gas (GHG) emissions have continued to rise from 1990 to 2019 (Figure 36), although there was a slower growth rate over the last decade compared to the period from 2000 to 2010.[iii] On the positive side, there is increased evidence of global climate mitigation action with currently more than 80 per cent of global greenhouse gas emissions covered by net-zero ambitions or announcements (figure 35).[97]

### THE CARBON BUDGET IS ALMOST SPENT

The term *carbon budget* is in principle the amount of carbon dioxide that can be emitted over a certain period to keep the global temperature increase within certain limits. The comparison is usually against pre-industrial times (1850-1900). Since 1850, the total cumulative $CO_2$ emissions have exceeded 2,400 $GtCO_2$.[iv] To limit the temperature increase to 1.5°C, the remaining carbon budget is estimated at 400 $GtCO_2$.[v] This is roughly the same amount as the emissions during the last decade. To restrict the global warming to 2°C, the remaining carbon budget is 2.9 times higher at 1,150 $GtCO_2$.[vi] This means that we must act immediately and implement emission reduction measures in all sectors. If not, it will be impossible to restrict the global warming to 1.5°C.

Built into the IPCC's carbon budgets are reductions in other greenhouse gases (e.g., $CH_4$, $N_2O$, $SF_6$, HFCs and CFCs) and aerosols. Methane ($CH_4$) is a very potent greenhouse gas, over 28 times as potent as $CO_2$ over a 100 years period, but is short-lived in the atmosphere. Aerosols (tiny particles or droplets in the air) have an intrinsic cooling effect on the climate, but the main source is combustion of fossil fuels, especially coal power, leading to a built-in global warming from the energy transition away from coal.

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[i] **Climate Change 2021:** The Physical Science Basis (AR6I) **Climate Change 2022:** Impacts, Adaptation and Vulnerability (AR6II) **Climate Change 2022:** Mitigation of Climate Change (AR6III) These will be followed by the final synthesis report which is expected to be published in 2023.

[ii] Originating from human activities

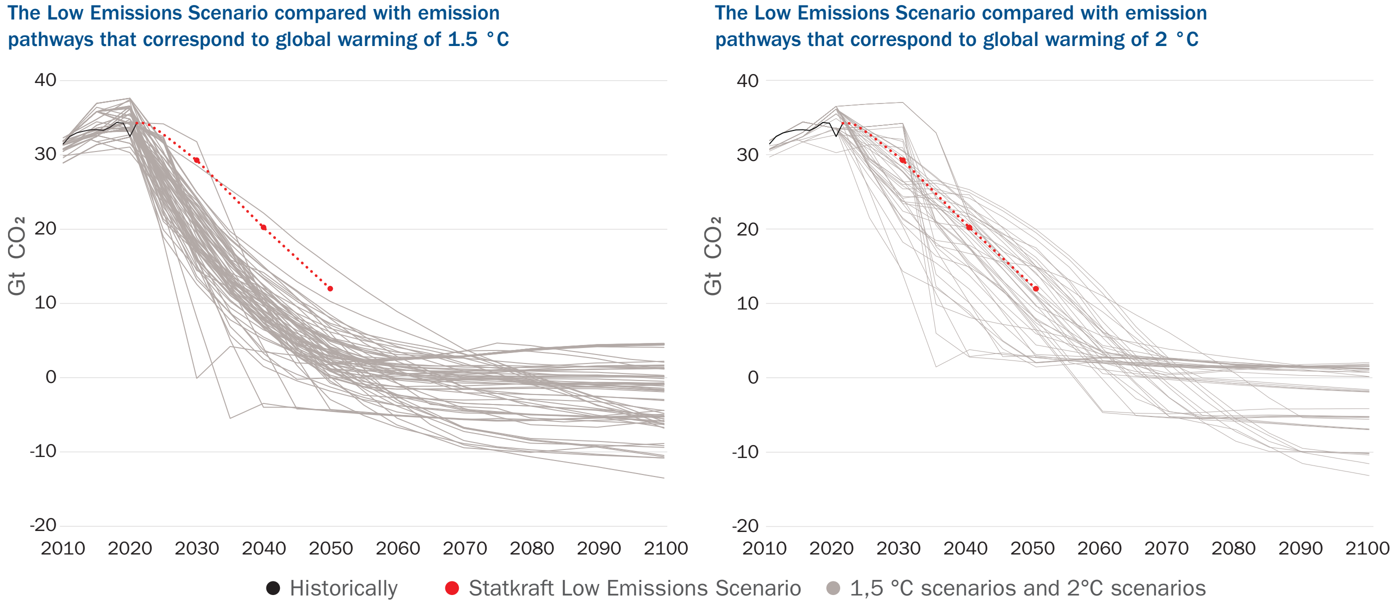
[iii] The greenhouse gas emissions growth 2010-2020: +1.3%/year, 2000-2010: +2.1%/year

[iv] With a 68% confidence interval

[v] With a budget uncertainty of ± 220 $GtCO_2$, with a 67% probability.

[vi] With a budget uncertainty of ±220 $GtCO_2$ with a 67% probability

**37** Emission pathways for energy-related $CO_2$ emissions [ii, iii, 100]



This warming effect from the reduced aerosols needs to be counteracted by a fast reduction in other greenhouse gases, like methane, but these are often more difficult to limit. According to IPCC, mitigation pathways limiting global warming to either 1.5°C or 2°C require that the GHG emissions peak already before 2025.

- Compared to 2019 levels, global GHG emissions must be reduced by 27 per cent within the next eight years, and 63 per cent by 2050 to follow 2°C pathways
- A 1.5°C pathway is more drastic with a reduction need of 43 per cent before 2030 and 84 per cent within 2050

## Comparing the Low Emissions Scenario with IPCC scenarios

When analysing the global energy systems, it is natural to draw comparisons between the Low Emissions Scenario and the mitigation pathways assessed by the IPCC AR6. We have compared the Low Emissions Scenario with the following three IPCC pathways: i) 2°C scenarios, ii) 1.5°C scenarios with overshoot (OS)[i] and iii) 1.5°C scenarios with limited/ no overshoot.[i] In general, we find that the same key solutions are chosen to decarbonise the energy system in all four cases, while there are some differences in absolute terms and the relative share of the different solutions.

### THE LOW EMISSIONS SCENARIO IS IN LINE WITH A 2°C EMISSIONS PATHWAY

The emissions analysed in the Low Emissions Scenario are energy-related $CO_2$ emissions. These are emissions from fuel combustion. Energy-related $CO_2$ emissions account for around three quarters of the global $CO_2$ emissions.[99] In the Low Emissions Scenario, global energy-related $CO_2$ emissions will fall by over 60 per cent between now and 2050, and we will end up with annual emissions of around 12 Gt$CO_2$ in 2050. This means that the energy-related $CO_2$ emissions in the Low Emissions Scenario are in line with the most recent IPCC's 2°C pathways, but still the reductions in emissions will neither be fast nor deep enough to achieve a 1.5°C pathways (Figure 37).[iii]

### THE LOW EMISSIONS SCENARIO IS IN LINE WITH THE IPCC SCENARIOS ON ELECTRIFICATION

Electrification and energy efficiency are the most cost-efficient ways of cutting emissions. These are also the main tools for cutting emissions in the Low Emissions Scenario and the share of electricity in final energy is in line with the median of the 2°C scenarios from the IPCC[iv] (Figures 38-41).

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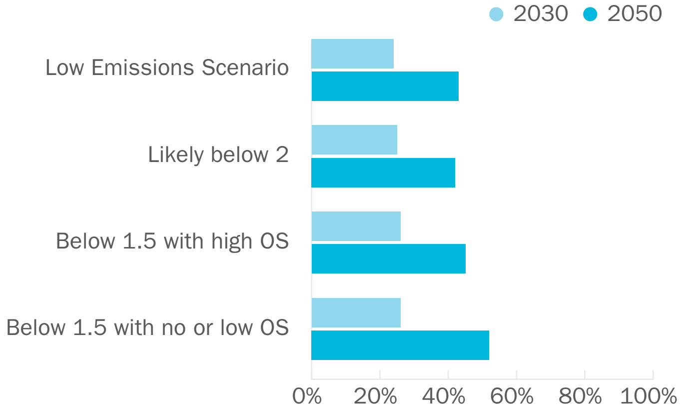
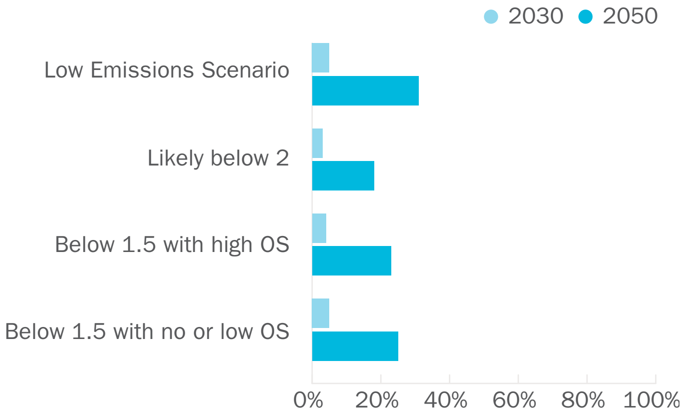
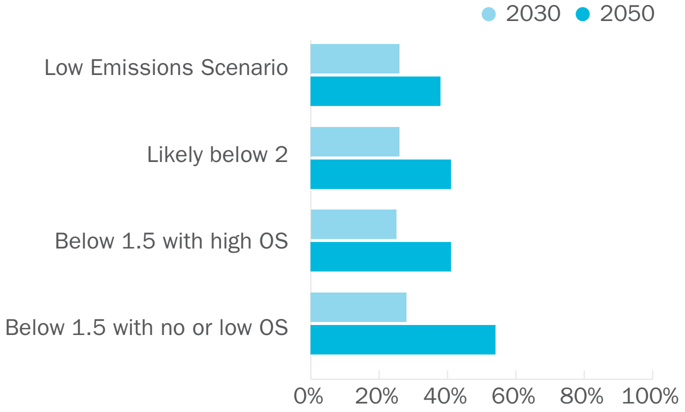
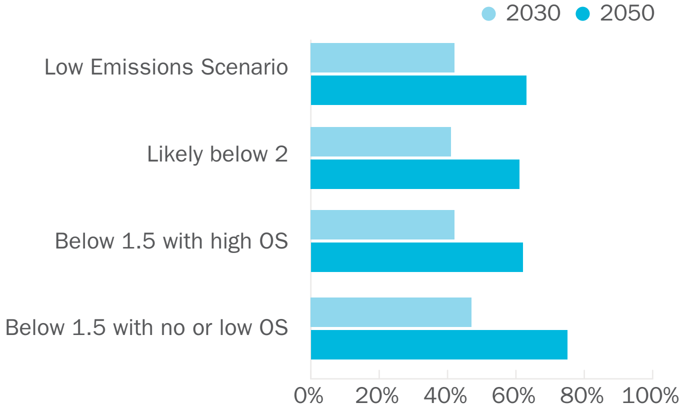
[i] A climate overshoot is a period where global warming increases beyond the temperature mark before it later cools back down.

[ii] The graphs have been prepared in cooperation with Glen Peters, Research Director, CICERO, and retrieved from the latest AR6 report and Statkraft's analyses

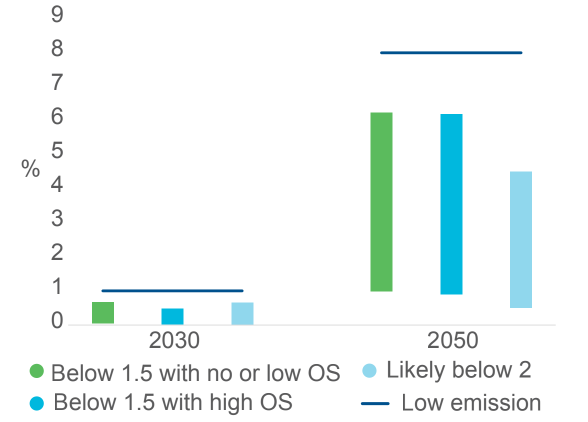
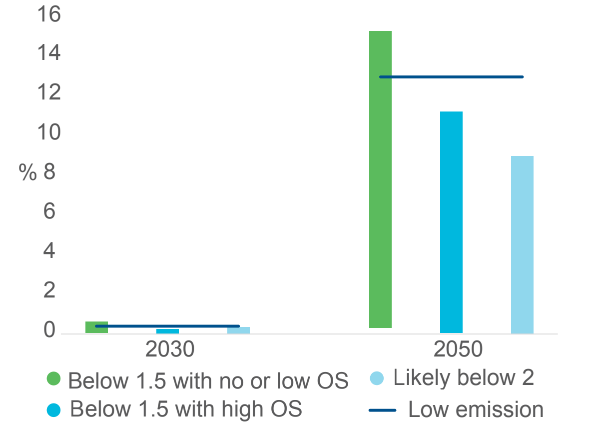
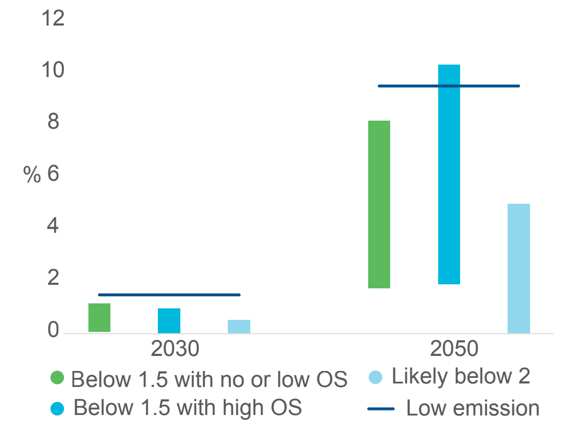
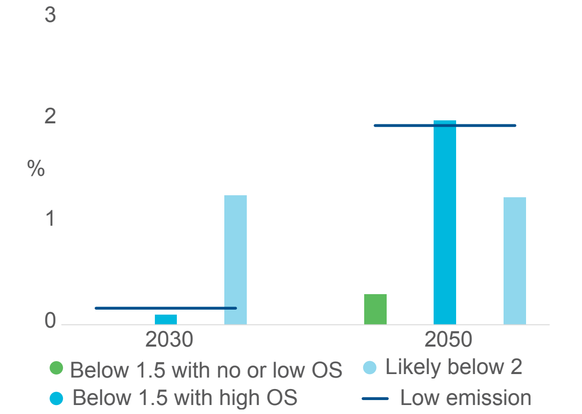
[iii] To say that emission pathways correspond to global warming of 1.5°C or 2°C is a simplification. The 1.5°C scenarios show energy-related $CO_2$ emissions from scenarios reported to the IPCC AR6, which with a 50 per cent probability or more will keep global warming below 1.5°C at the end of the century. We only show the scenarios that explicitly report energy-related $CO_2$ emissions. In the same way, the 2°C scenarios show the IPCC AR6 scenarios that with a 67 per cent probability will limit global warming to below 2°C. The uncertainty relates to assumptions about emissions and the time period that are not covered in the Low Emissions Scenario and on the impact of greenhouse gases on the global temperature.

[iv] Represents the median of a wide set of scenarios

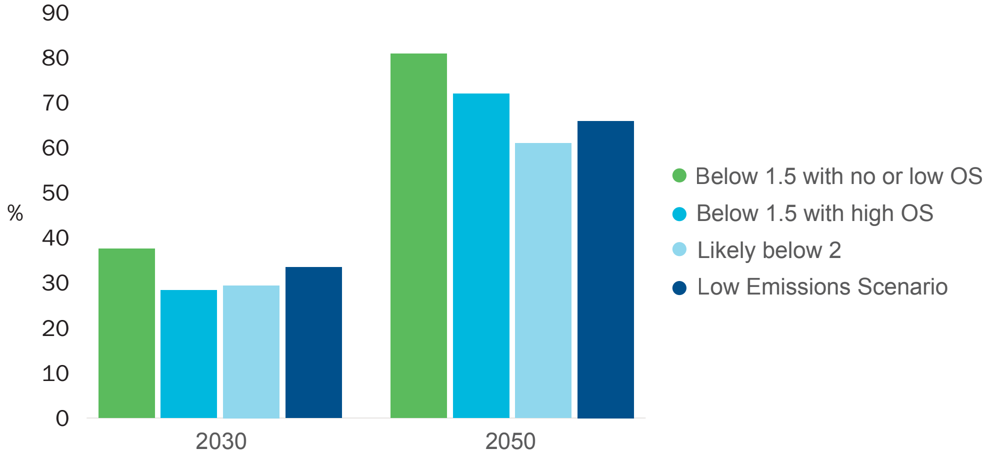
| | | |
|---|---|---|
| **Electricity in final energy** | For 2030, the share of electricity in final energy is almost identical in the four cases, whereas for 2050, the Low Emissions Scenario has a slightly higher share than the 2°C scenarios but is below the 1.5°C scenarios. | **38** Share of electricity in final energy (%) from the AR6III report compared to the Low Emissions Scenario<br><br> |
| **Transport** | Electric vehicles will be crucial for reducing emissions in the transport sector. In the Low Emissions Scenario, a 31 per cent share of electricity in final energy for transport is achieved in 2050, which is higher than the shares from the three IPCC scenarios. | **39** Share of electricity in transport (%) from the AR6III report compared to the Low Emissions Scenario<br><br> |
| **Industry** | For the industry sector, electrification is a key decarbonisation strategy for "lighter" manufacturing-oriented industries. For 2030, the Low Emissions Scenario is essentially identical to the three cases from IPCC, whereas the electricity shares for the 1.5°C scenarios with limited/no overshoot is considerably higher for 2050. | **40** Share of electricity in industry (%) from the AR6III report compared to the Low Emissions Scenario<br><br> |
| **Buildings** | Electrification of buildings is usually a cost-effective decarbonisation measure, especially when utilising heat pumps. The Low Emissions Scenario is essentially identical to the 2°C scenarios as well as the 1.5°C scenarios with overshoot for both 2030 and 2050. However, the 1.5°C scenarios with limited/no overshoot have higher shares of electricity in buildings during the period towards 2050. | **41** Share of electricity in buildings (%) from the AR6III report compared to the Low Emissions Scenario<br><br> |

**HYDROGEN USE IN THE LOW EMISSIONS SCENARIO IS CONSISTENT WITH 1.5 °C SCENARIOS**
Alternative energy carriers can contribute to the reduction of emissions in sectors that are difficult to electrify directly ("hard-to-abate"). Although not currently competitive for large-scale applications, it is expected that clean hydrogen will play a major role in decarbonising the global energy system.

The use of hydrogen in the Low Emissions Scenario is compared to the outcome space from the IPCC scenarios. The outcome space is defined as the values at the 25th and 75th percentiles in scenarios that limit warming to 2°C or 1.5°C. There are large uncertainties in the hydrogen deployment through the different IPCC scenarios. Limiting global warming to 2°C or 1.5°C means balancing between different measures. Although the Low Emissions Scenario is in the upper part of the outcome space for hydrogen, there are scenarios with much more hydrogen deployment needed as well.

| | | |
|---|---|---|
| **Hydrogen in Final energy** | The Low Emissions Scenario is relatively optimistic regarding clean hydrogen development. As seen, the share of hydrogen in final energy in the Low Emissions Scenario is a few percentage points higher than the upper values from even the most ambitious of the IPCC scenarios. Going sector by sector, the results are broadly in line with the upper values of the 1.5 °C scenarios. | 42 Outcome space for shares of clean hydrogen in final energy from the IPCC AR6 compared to the Low Emissions Scenario<br><br> |
| **Transport** | For the transport sector, the hydrogen share in the Low Emissions Scenario is essentially identical to upper value from the 2°C and 1.5°C scenarios in 2030. In 2050, the share in transport is 13 per cent, a few percentage points below the upper value from the 1.5°C scenarios with limited/no overshoot. | 43 Outcome space for shares of clean hydrogen in transport from the IPCC AR6 compared to the Low Emissions Scenario<br><br> |
| **Industry** | In addition to transport, industry is the sector in which it is expected that hydrogen can contribute the most.<br>In 2050, the share of hydrogen in final energy in the industry sector reaches 9.5 per cent in the Low Emissions Scenario. This is slightly behind the value from the 1.5°C scenarios with overshoot, but otherwise it is higher than the upper values from the other scenarios. Hydrogen use in industry feedstocks comes in addition. | 44 Outcome space for shares of clean hydrogen in industry from the IPCC AR6 compared to the Low Emissions Scenario<br><br> |
| **Buildings** | Hydrogen is expected to have a more modest role in decarbonising buildings, as a value of approximately two per cent is reached in 2050 for the Low Emissions Scenario, which is very close to the upper value from the 1.5°C scenarios with overshoot. | 45 Outcome space for shares of clean hydrogen in buildings from the IPCC AR6 compared to the Low Emissions Scenario<br><br> |

46 Shares (median value) of solar and wind power for the 1.5°C scenarios (with and without overshoot) and the likely below 2°C scenario from the IPCC compared to the Low Emissions Scenario. The figure compares the shares of solar and wind in electricity generation (%)

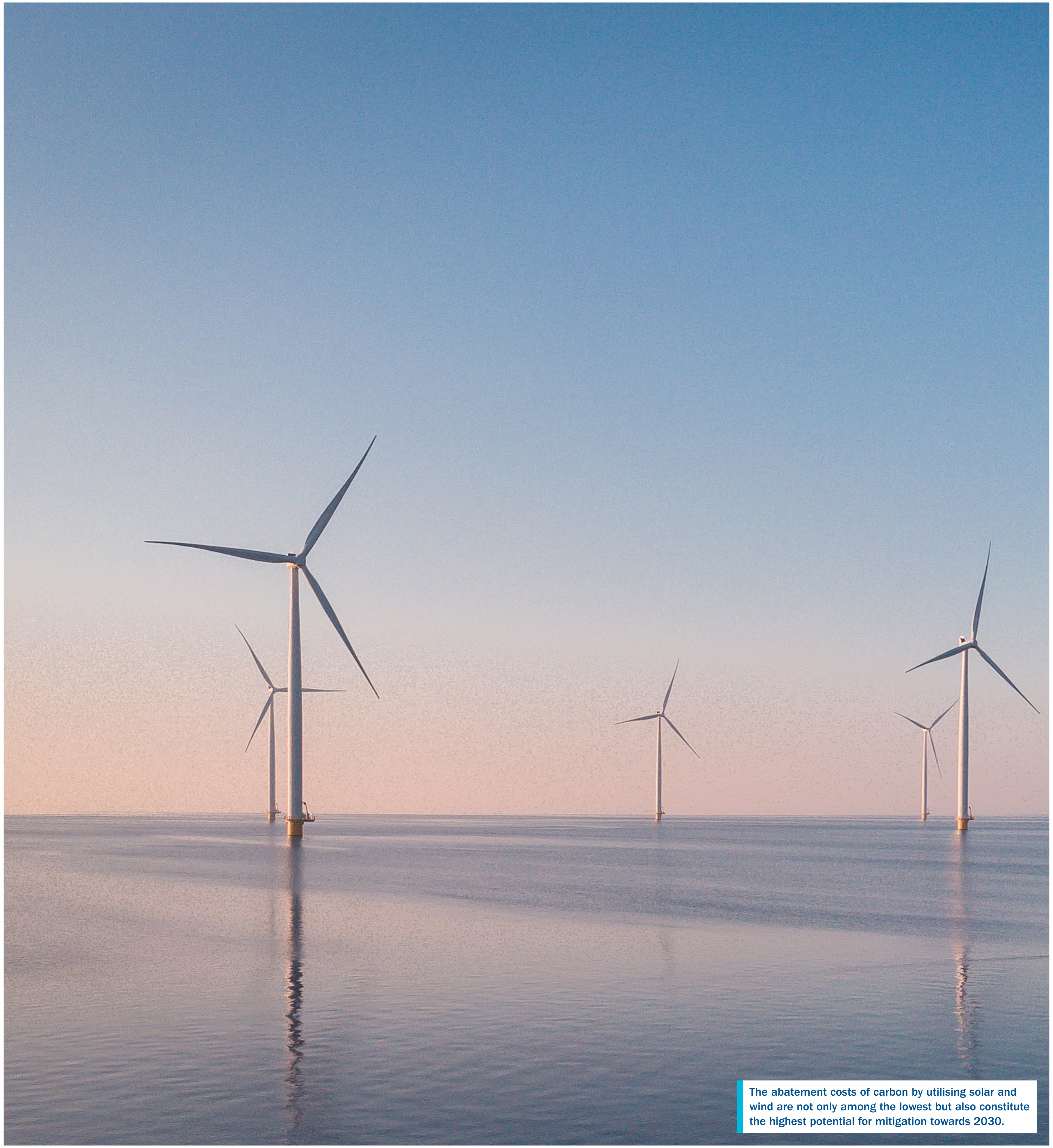


### SOLAR AND WIND GENERATION IN THE LOW EMISSIONS SCENARIO IS HIGHER THAN IN IPCC'S 2°C SCENARIOS

The abatement costs of carbon by utilising solar and wind are not only among the lowest but also constitute the highest potential for mitigation towards 2030. According to the IPCC AR6III report, mitigation options costing USD 100 or less per tonne of $CO_2$ equivalents removed could reduce global GHG emissions by more than 50 per cent before 2030, compared to 2019 levels. Additionally, half of these measures cost less than USD 20 per tonne removed, including a large contribution from the deployment of solar and wind power, along with energy efficiency improvements. Towards 2030, the share of wind and solar in power generation in the Low Emissions Scenario is higher or equal to the IPCC 2°C and 1.5°C scenarios with overshoot, while below the most optimistic 1.5°C.
In 2050, the Low Emissions Scenario reaches a total share of 66 per cent, higher than the 2°C scenarios (Figure 46).

### THE LOW EMISSIONS SCENARIO COMES A LONG WAY – BUT NOT ALL THE WAY TO 1.5 °C

In the Low Emissions Scenario, the emissions pathway is consistent with a global warming of 2°C. In addition, the level of solar and wind, electrification and clean hydrogen are on par with even more ambitious IPCC pathways. However, every $CO_2$ molecule counts, so to restrict the temperature increase to 1.5°C, the transition needs to accelerate beyond what is assumed in the Low Emissions Scenario. To reach net zero, the last and most expensive $CO_2$ molecule needs to be handled. As these last molecules are extremely difficult to avoid, virtually all 1.5°C scenarios include carbon dioxide removal solutions towards 2050 and beyond, such as from afforestation, bioenergy with CCS and Direct Air Capture technologies.



**The abatement costs of carbon by utilising solar and wind are not only among the lowest but also constitute the highest potential for mitigation towards 2030.**

The European energy deficit challenges energy security, and causes substantial energy poverty. Strong and immediate action from policy makers to mitigate the most serious outcomes is needed in the near term.

# A year of unprecedented challenges should accelerate the energy transition

In a time of war, with an ongoing energy crisis and extreme political uncertainty, predicting the development of energy markets is more difficult than ever. The pace of political decisions has accelerated in Europe and elsewhere, as the vulnerability of fossil-based energy systems has become painfully evident. The European energy deficit challenges energy security, and causes substantial energy poverty. Strong and immediate action from policy makers to mitigate the most serious outcomes is needed in the near term.

In the longer term, the energy crisis has shown that a rapid transition to renewable-dominated energy systems is imperative to improve resilience and energy security, reducing countries' dependence on unstable political regimes and volatile fossil fuel markets. It is clearer than ever that renewable energy and energy efficiency are the main solutions to address the energy trilemma of sustainability, affordability and security of supply. In the fight against climate change, the current energy crisis may eventually turn out to be a tipping point.

In addition to the severe energy crisis, 2022 has seen extreme weather events cause serious damage in many regions of the world. These events have a devastating impact, but may also increase people's awareness of the need for a swift green transition. In Statkraft's Low Emissions Scenario, the drive of the public opinion and politics on one side, and markets and technologies on the other, reinforce each other and drive the energy transition towards a 2-degree pathway. The fastest way of cutting emissions is through enhanced energy efficiency, renewable power investments and electrification of energy use in transport, industry and buildings.

The energy transition will bring many technological tipping points in the coming years. Solar and wind power technologies are already the cheapest power generating technologies in most parts of the world, and electric vehicles will become cost-competitive with conventional cars in the next few years. In the Low Emissions Scenario, green hydrogen becomes cost-competitive compared to its fossil counterpart around 2040. These shifts to cleaner and more sustainable solutions do, however, require that policies and market forces work in tandem and that collaboration across sectors and countries is enhanced. In the conflicted world we see today, the need for strong international cooperation has never been more pressing.

# Appendix

## APPENDIX 1
## Key parameters in the Statkraft Low Emissions Scenario, compared with IEA and BNEF [101]

| Sectors | Statkraft's Low Emissions Scenario 2022 | IEA STEPS (2021) | IEA Net zero (2021) | BNEF NEO (2021) Green Scenario |
|---|---|---|---|---|
| **Annual growth in primary energy demand 2020-50** | -0.20 % | 0.78 % | -0.27 % | -0.17 % |
| **Power sector** | | | | |
| **Power demand, annual growth 2020-50** | 2.9 % | 1.87 % | 3.31 % | 5.41 % |
| **Wind power, annual growth 2020-50** | 8.7 % | 5.86 % | 9.57 % | 13.3 % |
| **Solar power, annual growth 2020-50** | 11.5 % | 8.51 % | 11.8 % | 11.3 % |
| **Hydropower, annual growth 2020-50** | 1.6 % | 1.47 % | 2.24 % | - |
| **Fossil share in power sector (TWh, 2050)** | 11.5 % | 31.9 % | 0.36 % | 0,0 % |
| **Primary energy** | | | | |
| **Oil consumption: annual growth 2020-50** | -2.8 % | 0.49 % | -4.56 % | -5.77 % |
| **Gas consumption: annual growth 2020-50** | -0.67 % | 0.78 % | -6.69 % | -6.17 % |
| **Coal consumption: annual growth 2020-50** | -3.83 % | -0.93 % | -12.06 % | -12.4 % |
| **Global energy-related $CO_2$ emissions ($GtCO_2$) in 2050** | 12.0 | 33.9 | 0,0 | 0,0 |

## APPENDIX 2
## Assumptions and overview of emissions covered in the Low Emissions Scenario

Statkraft's Low Emissions Scenario extends current global energy trends up to 2050. The scenario is based on the expansion of known technologies and on Statkraft's own global and regional analyses. The scenario is not based on a linear projection of current trends, nor does it base itself on a given climate target and perform a backwards analysis from that point.

The Low Emissions Scenario analyses the development in costs for known technologies up to 2050, including renewable power production, batteries, emission-free hydrogen, etc. The scenario assumes a continued steep fall in costs per MWh and a fast pace of development until around 2030. The cost decline then slows somewhat, first for wind power and then for solar power.

The analyses are based on internal models as well as in-depth studies of external sources. Statkraft's Low Emissions Scenario has been prepared by Statkraft's strategic analysis team in co-operation with experts in other fields. Over 50 personnel are involved in market analysis in Statkraft.

The scenario combines a global energy balance model and a European energy system model with insights from detailed power market models in the countries where we are active. Statkraft models power markets in detail, hour by hour, for the Nordic countries, Europe, India, and countries in South America up to 2050.

The starting point for the analyses is economic growth and population growth in line with a market consensus. In the Low Emissions Scenario, we have assumed that the growth rate in the economy will recover, however, the global economy and demand for energy are expected to remain lower over the entire period compared to expectations before the COVID-19 pandemic and the war.

### WHICH EMISSIONS ARE COVERED IN THE LOW EMISSIONS SCENARIO?

The emissions analysed in the Low Emissions Scenario are energy-related $CO_2$ emissions. These are emissions from fuel combustion (excluding the incineration of non-renewable waste). Other emissions that are not included are diffuse emissions (i.e., leaks emissions from the transport and storage of fuel, etc.) and industrial process emissions. Process emissions are emissions from chemical reactions in the production of, for example, chemicals, cement, and certain metals. These emissions are not from combustion and cannot therefore be reduced by using electricity instead of fossil fuels. These are not included in the Low Emissions Scenario.

$CO_2$ emissions from land use, land use change and forestry (LULUCF) and other greenhouse gases are also excluded from the Low Emissions Scenario.

The emissions are broken down into the power sector, buildings sector, transport sector, industry sector and a category for other sectors:

- **Power:** Emissions from power plants, heating plants and combined power and heating plants.
- **Buildings:** Emissions from residential, commercial, and institutional buildings, as well as other unspecified buildings. Such emissions include, but are not limited to, heating and cooling rooms, heating water, lighting, cooking appliances and other appliances.
- **Transport:** Emissions from the transport of goods and people, including emissions from transport on public roads or by rail, domestic sea transport and domestic air transport. Emissions from the transport of fuels through pipelines are not included. Emissions from international transport are covered at an international level.
- **Industry:** Emissions in connection with the combustion and production of heat in the manufacturing and construction industries. This includes emissions from iron and steel production, the chemical and petrochemical industry, cement and the pulp and paper industry. Emissions from vehicles that are not used on public roads and heating of industry buildings are also included.
- **Other sectors:** Emissions from energy use in agriculture, in addition to emissions from the production and transformation of fuels, i.e., emissions from, for example, oil and gas production, coal mines and petroleum refineries. Agriculture entails energy-related emissions from farming, forestry, and fishing.

## APPENDIX 3
## ETM Model description

The Statkraft Energy Transition Model (ETM) has been used to analyse different European pathways of the REPowerEU plan. ETM is a techno-economic optimisation model covering the entire energy system of 29 European countries/regions, especially suited to analyse complex interactions between supply and demand of energy. The model is based on GENeSYS-Mod developed by Technische Universität Berlin ("Designing a Model for the Global Energy System — GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)" by Konstantin Löffler, Karlo Hainsch, Thorsten Burandt , Pao-Yu Oei, Claudia Kemfert, and Christian Von Hirschhausen (2017).

For modelling purposes, we have assumed that imports will be used to cover the hydrogen demand within refineries, petrochemical industry, and blast furnaces. Domestic hydrogen production is modelled to primarily be used for industrial heat production, transport, synthetic fuels production, power generation, and blending with fossil gas.

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