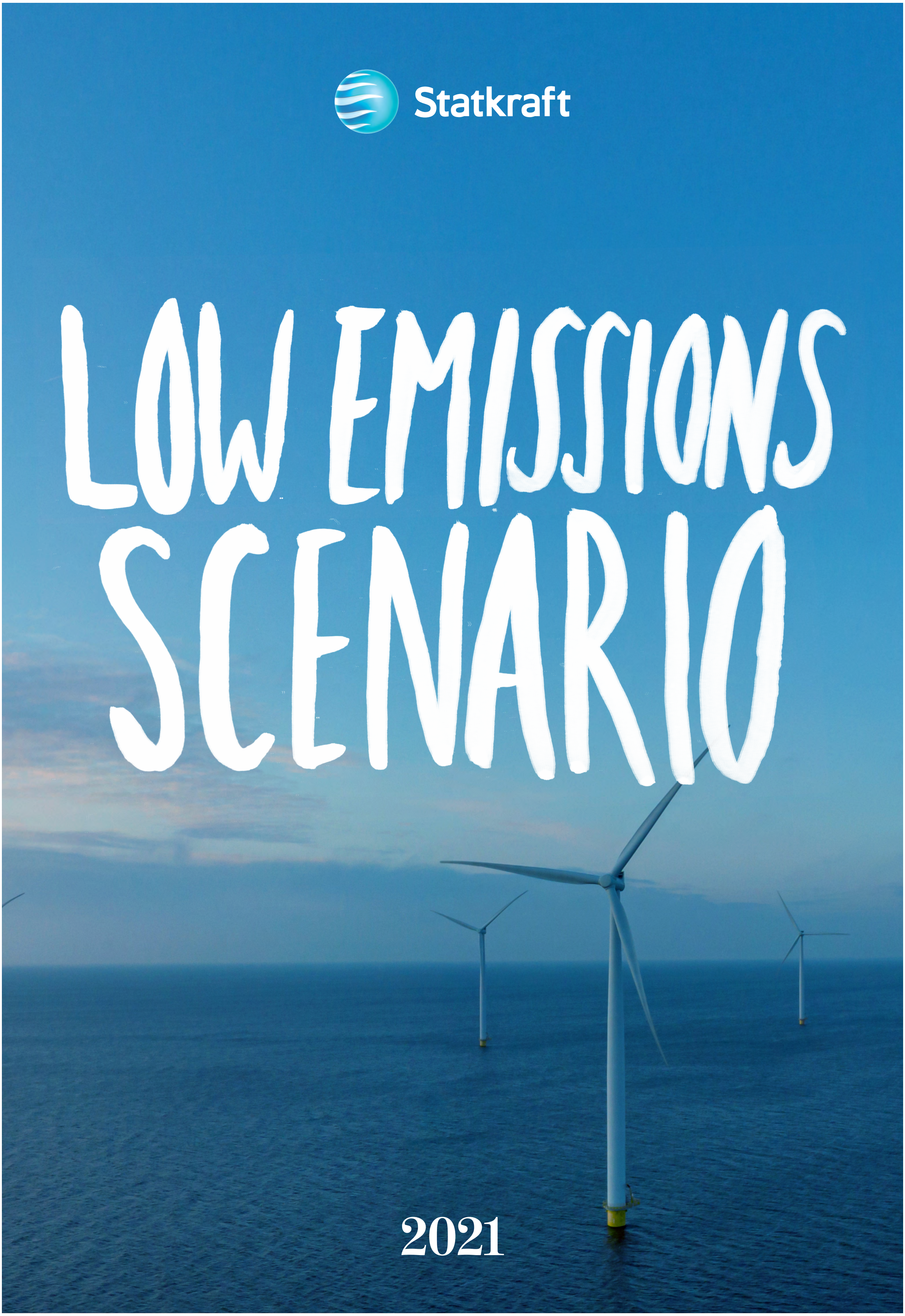
Statkraft

LOW EMISSIONS SCENARIO



2021

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Summary of Statkraft's Low Emissions Scenario 2021

Falling costs for renewable technologies together with stronger climate policies will result in carbon emissions in line with a 2 °C pathway. Stopping global warming at 1.5°C, however, will require a substantial increase in both political ambitions and pace of global action.

Regional hydrogen markets and seasonal storage become increasingly attractive with more wind and solar power production.

40 %

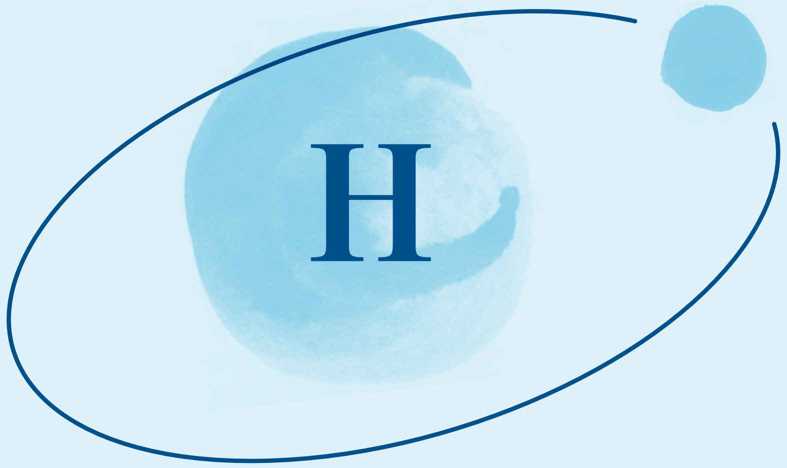
2020 was a good year for electric vehicles. Global sales of battery-electric cars increased by 40%, even though total car sales fell.

2050

2020 had a record high buildout of solar and wind power. Even so, we need to install more than twice as much every year to 2050 to limit global warming to two degrees.

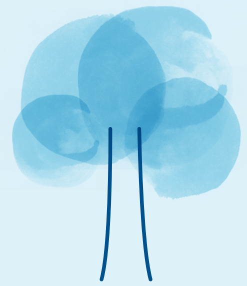
60 %

The costs of electrolysers will fall by 60% within 2050. Falling costs of renewable energy and electrolysers will make an increasingly attractive business case for green hydrogen.

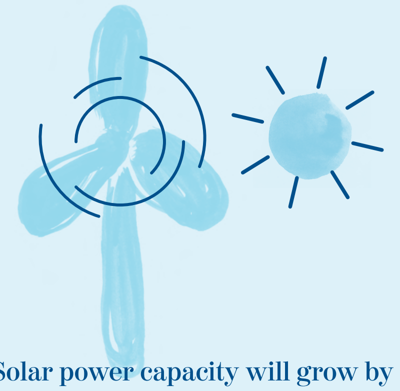


Hydrogen will play a significant role in the 2050 energy system. In the Low Emissions Scenario, power demand increases by ten percent globally in 2050 from green hydrogen production

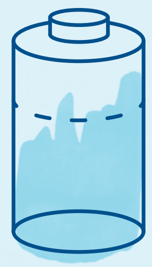
Green investments increased in 2020 despite the economic downturn caused by the pandemic. Investment in renewable power was (7%) higher in 2020 than in 2019.



Green hydrogen is necessary to limit climate change to Paris Agreement levels.



Solar power capacity will grow by a factor of 21, and wind power by a factor of 7 between today to 2050.



Solar and wind power will supply about two thirds of the global power system.

Electrification is the main solution for cutting CO_2 emissions. The share of electricity in final energy demand will more than double toward 2050.

Norway is in a special position in the world with a high share of flexible hydropower and an already emission-free power sector.

It's time to speed up the green transition

Christian Rynning-Tønnesen

We are in the midst of a renewable energy revolution. Solar and wind power are edging out competitors in their offer for affordable renewable energy to the world, while hydropower is gaining importance as an emissions-free and flexible resource. The great powers from East to West are strengthening their climate ambitions, with Europe taking a decided lead. Pressure is on to cut emissions across industry, transportation, and construction, while other new, renewable forms of energy, such as green hydrogen, are emerging as part of the solution. Development is happening fast, but it needs to go even faster.

For the sixth consecutive year, we have released Statkraft's Low Emissions Scenario – our analysis of the energy world towards 2050.

Statkraft's Low Emissions Scenario has previously stood out due to its optimistic perspective, showing that the markets – when supported by predictable climate policy – can make significant strides in the energy transition and in cutting greenhouse gas emissions. At the same time, the analysis in our report is realistic, as it doesn't build upon assumptions related to aggressive global climate policies or breakthroughs in yet unknown technologies.

Today we see that our Low Emissions Scenario offers a realistic perspective of the future, in line with continued strong market trends. The developing trends that were considered optimistic just a short while ago are now firmly positioned in the mainstream.

It's clear that the combination of solid market development and predictable climate policies can take us far. It can help us cut emissions and get the world on a two-degree track. This year's analysis projects lower energy-related CO2 emissions than ever before. But it's still not enough. And if the trends continue as predicted in the Low Emissions Scenario, emissions will stay in line with the UN Climate Panel's two-degree trajectory.

Currently, the Earth's temperature is 1.1 degrees warmer than it was during pre-industrial times, and we are already seeing the effects of climate change in the form of extreme heat, wildfires, and violent floods. The UN Climate Panel's sixth report, released in August 2021, made us even more acutely aware of how a temperature increase of two, three and four degrees will have dramatic consequences for our planet. Every decimal count in this fight. Two degrees is simply too much. We need to limit global warming to a level as far down towards 1.5 degrees as possible

During the coronavirus pandemic in 2020, a time when our lives were upended and we lived in lockdown, we experienced a six percent drop in CO2 emissions. That's the very amount that we must reduce year-on-year towards 2050, if we are to reach the Paris Agreement's target of 1.5 degrees.

To reach a two-degree target, we will need ambitious and predictable political involvement: high carbon prices and a transition to renewable energy in people's housing, transport, and work. However, reaching a 1.5-degree target will require much more, including more powerful reinforcement of climate policies, compounded by real action. Compared to a Low Emissions Scenario with a 2-degree course, a 1.5-degree path means much more of everything – a lot faster.

As climate ambitions increase, the focus will broaden from renewable power and electric cars, where existing policies together with the market and technology drive much of the transformation, to other sectors such as industry and long-distance transportation, where cutting emissions is a more demanding endeavour. These sectors will depend on even more political might, and the use of clean hydrogen will play an important role in reaching climate goals across heavy industries. This year's Low Emissions Scenario takes a closer look at hydrogen. It is already considered an important climate solution, but it must be scaled up much faster to meet a 1.5-degree temperature trajectory.

In this year's report, we reflect on development trends that have emerged over the past year, including insight into climate policies in central parts of the world. The current policies in several countries can contribute to realising the Low Emissions Scenario, but there is a need for policies that push for faster implementation of net zero solutions.

Chapter two in the Low Emissions Scenario outlines the very scenario to which the report title refers, showing that we need all the renewable energy sources (sun, wind, and water) in play to achieve our climate goals. Urgently. In chapter three, we dive into clean hydrogen, an energy source that's becoming increasingly important as we strive towards a net zero future.

The world is taking the necessary, critical steps towards a green shift, but we need to pick up the pace. This year's Low Emissions Scenario shows that the rapid scaling of renewable energy and green solutions leads to significant emissions reductions. But this optimistic perspective in our report comes with some clear solutions towards the end, specifically related to clean hydrogen.

We hope that our Low Emissions Scenario can contribute to an increased understanding of where we are today and what is needed to transition to a greener energy future.

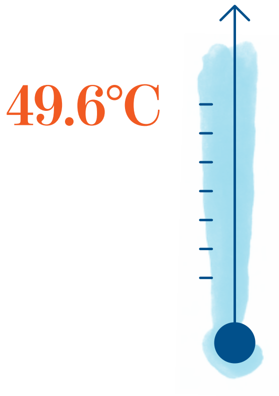
1

ENERGY TRANSITION WITH A MORE COMPLEX GREEN AGENDA

Nations are strengthening their climate targets, but even so, it is not enough to limit global warming to 1.5°C.

The post pandemic energy world: A more complex green agenda

In this chapter, we take a closer look at climate and energy trends of the past year, such as the many extreme weather events, the new report from the Intergovernmental Panel on Climate Change (IPCC) , and the latest climate policies in Europe, China, US, and India. We see positive signs in many countries; climate targets are strengthened, and policies are implemented to support the energy transition. However, we do also see that the speed and momentum in the energy transition are insufficient. The 1.5°C target will not be reached without a significant policy push. Renewables need to be rolled out faster and concrete actions to scale up other clean technologies are needed. Clean hydrogen is one such solution, and is further addressed in chapter 3 of this report.



49.6°C was measured in June in Canada, which is a new record

At the end of July this year, there were over 80 forest fires in western USA

A climate crisis is looming

In the shadow of the pandemic, 2020 was a historically warm year and marked the end of the warmest decade on record, thus continuing the trend dating back to 1980 of successively warmer decades. The current global temperature is estimated to have climbed about 1.1°C since pre-industrial time. Nowadays, more is known about the impacts of global warming, and it is increasingly more apparent that greenhouse gas emissions risk causing damage that is impossible to repair.[1]

This summer has given us further insight into how global warming affects the weather. A scorching heat wave has been seen along the west coast of the United States and Canada. Temperatures of up to 49.6°C have been measured in Canada, which is a new record. High temperatures and low rainfall have sparked a number of wildfires, with more than 80 active forest fires on the United States' west coast towards the end of July. Heavy wildfires also hit Brazil and Greece.[2]

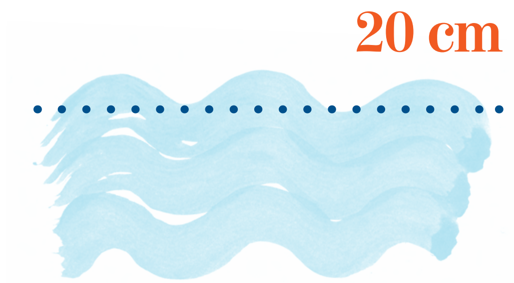
Global warming is also causing heavy rainfall. Chinese local authorities have reported over 300 deaths following heavy rains and flash floods this summer. Over the course of just three days, Zhengzhou experienced the equivalent of one year's rainfall. In India, over 100 people died this summer as a result of landslides and flash floods triggered by heavy rains. Europe has also seen heavy rainfall and flash flooding this summer. Germany and Belgium in particular have been hit hard.[3]

The extreme weather events described here are only a sample of what has taken place. In isolation, it is difficult to attribute climate change to a single event, but the science covering this field is advancing. Heatwaves, like the one in Canada, is assessed to be 150 times more likely today with a 1.1°C global warming compared to pre-industrial time.[4]

On 9 August, the Intergovernmental Panel on Climate Change (IPCC) of the United Nations presented the Sixth Assessment Report. It provides an update on climate change based on the latest within climate science. The report concludes that we are already experiencing the impacts of a changing climate. Global land precipitation has increased since 1950, and the increase has been picking up pace since 1980. The number of extreme heat waves has also increased since 1980 and will be exacerbated by further global warming. With a global warming of two degrees, the current "ten-year heatwaves" will happen in average every second year. In addition, the extreme heatwaves will get even hotter, and heavy precipitation will increase in frequency and intensity.[5]

The IPCC believes it is possible to limit global warming to 1.5°C, but this will require dramatic and rapid change. Either way, society will need to be adapted to a different climate. Even in the most optimistic scenarios adaptation will be needed. Hydropower can help to limit the harmful effects of more extreme weather if the river systems are regulated, particularly by avoiding extreme amounts of water in connection with floods. Despite the need for adaption to cope with the climate changes, this cannot replace emission reductions. Comprehensive, rapid and powerful climate policy and action is needed.

In the course of three days, the same quantity as one year of rainfall happend in Zhengzhou, China



The average sea level rose by 20 cm between 1901 and 2018, and the rate of the sea level rise is increasing

Living with the escalating ramifications of climate change in our day-to-day lives may gradually influence voters' views on climate policy. As extreme weather events become more common, media coverage of the impact of climate change is increasing, which in turn is pushing it up the political agenda. Major material damage will drive up the costs of climate change for businesses and society. There is therefore reason to believe that more extreme weather will lead to a stronger climate policy. In Europe, climate change has been one of the most important concerns in public polls. In this year's edition of the Eurobarometer survey, which was released in March and April 2021, 93 per cent of respondents considered climate change to be a serious or very serious problem and they support the European ambition of net zero emission in 2050. This is key, because of the need for public support to be able to implement an ambitious climate policy.[6]

COVID-19 – changing conditions for the energy markets

The COVID-19 pandemic hit hard in 2020 and continues to do so in 2021. As of September 2021, there have been more than 200 million confirmed cases of COVID-19 globally, including more than 4.7 million deaths.

The political response to the pandemic has varied between countries, but throughout the world, stringent measures have been put in place at various times to limit the spread of the virus. Strict government measures and changes in behaviour in an attempt to prevent the spread of infection have led to a sharp economic decline.

The International Monetary Fund (IMF) estimates a global growth contraction of -3.5 per cent for 2020. The energy markets have also been hit by the pandemic. In 2020, energy demand fell by 4 per cent, where the demand for oil had the biggest fall, with a 9 per cent drop. So far in 2021 we have seen an increase in economic activity as the different economies reopened, which also is reflected in higher energy demand.[7]

Despite the economic downturn in 2020, global investment in green technologies increased. Investment in renewable power production increased by seven percent. There was also a 28 per cent increase in investments in electric cars and charging infrastructure in 2020. In addition, relatively large investments were made in heat pumps, batteries, hydrogen and carbon capture and storage (CCS).[8]

We see that the view of national debt has changed since the financial crisis. During the COVID-19 pandemic, there has been greater acceptance of stimulating the economy through increased government spending. The IMF has also urged countries not to end support measures too soon. In the United States, a number of stimulus packages were introduced in 2020, resulting in a record budget deficit of 14.9 per cent of GDP. The deficit in 2021 is expected to exceed 10 per cent of GDP. In Europe, it has been agreed that parts of the EU stimulus package of EUR 750 billion will be loan-financed through bonds issued by the European Commission. This permission from the member states for the European Commission to grant loans is a major change in the EU framework. Many of the stimulus packages aim to restart the economy, cut greenhouse gas emissions and foster sustainable development in a broad sense. Opinions are divided on the green credentials of the stimulus packages. Many of the packages include support for investment in renewable energy and green technology. However, existing CO_2 emitting sectors have also received considerable support. Politically, it will be a carful balancing act to facilitate the needed change with job security and economic growth.[9]

Increasing the capacity for public spending can make it easier to fund climate measures in the short term. It also gives more possibilities to ensure a fair transition by compensating those who lose out as a result of the change. Nevertheless, it is important that the climate policies are targeted and cost-effective. A transition to a low-emission society requires major investment, both private and public funds are needed. A strong economy will make it easier for groups that need to adjust to find new jobs and will generate tax revenues that can be used to support those who need help.

COP26 – net zero emissions targets are announced

The Paris Agreement, which came into force in 2020, is based on a five-year cycle in which the Parties to the treaty set out increasingly ambitious climate targets. Although the current nationally determined contributions (NDCs) are not sufficient to limit global warming to a maximum of 1.5°C, a gradual strengthening of global climate policy can move the world closer to this goal. In October 2018, the IPCC published a special report on the 1.5°C target. The report concluded that global CO_2 emissions must reach net zero around the middle of this century in order to limit global warming to 1.5°C higher than pre-industrial levels. This was again emphasised in the IPCC's report released in August 2021.[10]

Ahead of the next climate summit (COP26) in Glasgow, several large countries announced a long-term goal of net zero emissions. The countries that have adopted or are discussing a net zero ambition currently account for two thirds of the world's greenhouse gas emissions. In addition to long-term goals, several countries have increased their short-term ambitions. The fact that long-term goals are followed up with targets and specific plans in the short term gives climate policies a greater legitimacy and shows that words are followed up with action.

The think tank that produces the Climate Action Tracker estimates that with the targets set out in the Paris Agreement, global warming will be limited to 2.4°C by the end of the century. If the targets announced, but not yet incorporated into the Paris Agreement, are met, global warm-

1 Countries and nations with ambitions of net zero emissions[12]

Andorra
Argentina
Barbados
Bhutan
Brazil
Cabo Verde
Canada
Chile
China
Colombia
Costa Rica
Dominican Republic
European Union
Fiji
Grenada
Iceland
Indonesia
Jamaica
Japan
Kazakhstan
Laos
Malawi
Maldives
Marshall Islands
Mauritius
Monaco
Namibia
Nauru
Nepal
New Zealand
Norway
Panama
Seychelles
Solomon Islands
South Africa
South Korea
Sri Lanka
Suriname
Switzerland
Ukraine
United Kingdom
Uruguay
US
Vatican City

Afforestation & reforestation are two ways to achieve negative emissions, but not without challenges

ing will be limited to 2°C. As the IPCC again stated in August, rapid and massive emission cuts are needed if the world is to successfully limit global warming to 1.5°C. This requires countries to set more ambitious long-term goals, even though introducing more stringent shorter-term policies is even more important if global emissions are to fall rapidly.[13]

A goal of net zero emissions in 2050 on its own is not enough. What we do before and after 2050 is also crucial to limiting global warming to 1.5°C. After CO_2 is emitted into the atmosphere, it remains there for hundreds of years, and global warming is therefore a result of the cumulative emissions. The term 'carbon budget' is often used, which describes how much CO_2 can be emitted if global warming is to be limited to a certain level. The longer we wait to cut CO_2 emissions, the more negative emissions we will need.

There are several ways to achieve negative emissions through CO_2 removal. A natural solution is to absorb CO_2 through photosynthesis with for example afforestation. Afforestation is difficult because the forest needs to live for a long time before it can contribute to the permanent removal of carbon, there must be a net forest growth and biodiversity and sustainability must be taken into account. A technological solution is bioenergy with CCS. This is expensive and technologically complicated, in addition the bioenergy is needed in sectors that are difficult to electrify and the bioenergy needs to come from sustainable sources. Other technological solutions, such as removing carbon dioxide from the atmosphere, are currently at the demonstration stage and are far from being commercialised.

The measures for limiting CO_2 emissions vary in different parts of the world, but some trends can be seen. Many countries have pledged to increase the share of renewable energy, particularly in the power sector. Another trend is the increase in the use of carbon pricing schemes and carbon markets. In 2010, just over 5 per cent of global emissions were covered by carbon pricing. In 2021, this figure was in excess of 20 per cent, and this is expected to increase further. However, prices are too low in many cases to drive clean technology investment on their own.[14]

The next international climate negotiations, COP26, in Glasgow will give an indication of whether there is sufficient global determination to strengthen climate policies and to strive to limit global warming towards 1.5°C. It also remains to see whether there will be an agreement regarding the use of market mechanisms and cooperation between countries.

1

Publications from IEA and IPCC impact the climate debate

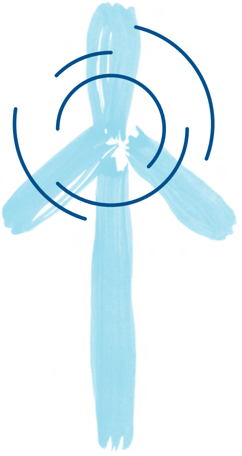
Both IEA and IPCC have published important reports during the year that have impacted the debate about energy and climate

IEA published the "Net zero by 2050" report as one of their contribution to COP26 that is held in Glasgow this November. The report describe how we can limit the global warming to 1.5°C, but the path is narrow and extremely challenging for all stakeholders. It requires immediate actions on a large scale in all polluting sectors. This compliments the first working groups contribution to IPCCs sixth main report on the physical science basis of climate change. It concludes that every additional tenth of a degree will have a large negative impact.

Since the world already have become 1.1°C warmer, a large proportion of the carbon budget for a 1.5°C target have been used already. To have a 50 per cent chance of achieving the 1.5°C target, we can only emit additional 500 $GtCO_2$ into the atmosphere. To have 50 per cent chance of achieving the 2°C target, we can emit 1350 $GtCO_2$. Both targets will be challenging to achieve, but the carbon budget is more than halved for a 1.5°C target compared to a 2°C target.

With only 500 $GtCO_2$ remaining, emissions will have to drop faster, and we need to achieve net zero emissions no later than 2050. This has a big impact on the energy sector, climate policies and the climate debate. It is not only the power sector that needs to decarbonize fast, the whole energy sector needs to do so, and that is one reason why hydrogen have gotten larger attention.

It has also a big impact on the future demand for fossil fuels. According to IEA, no new oil and gas field are needed in the net zero pathway. Climate organizations and think-tanks that long have pointed out the contradiction between new oil and gas field and the 1.5°C target has now support from IEA. The reports from IEA and IPCC has set important premises for the climate summit in Glasgow in November.



Falling costs for renewable energy has slowed down development of coal power more than expected

It will be easier to set more ambitious climate targets when the cost of cutting emissions is lower

Falling technology costs and high climate ambitions reinforce each other

Although multiple countries have set net zero targets, the world is still not keeping pace with the ambitions of the Paris Agreement. Nevertheless, considerable progress has been made, and the world is now closer to limiting global warming to 2°C than it was at the start of the last decade. Ten years ago, the IEA estimated that the political ambitions and technology costs at that time (Stated Policy Scenario) would lead to global warming in excess of 3.5°C. In November 2020, the IEA estimated that a similar scenario will 'only' lead to 2.7°C global warming, which is a major improvement, but still a long way off the Paris Agreement's target of well below 2°C.

An important driver for this has been falling costs in renewable energy such as solar and wind power, which have slowed down the expansion of coal power more than expected. This cost decline is the result of an active climate policy being pursued in many countries. If the temperature increase is to be limited to 1.5°C, this development needs to continue and extend to other sectors.[15]

The falling technology costs will make it easier to set more ambitious climate targets, and the cost of cutting emissions will decrease. Additionally, a more ambitious climate policy will make it more profitable to invest in clean technologies, and this in turn will lead to higher volumes and decreasing costs. This dynamic is at the core of Statkraft's Low Emissions Scenario.

A good example of this was seen when in 2019 the British Climate Change Committee estimated the costs of increasing the British climate target from an 80 per cent reduction by 2050 to net zero emissions by 2050. They concluded that they could meet the target of net zero emissions at the same cost. Since 2008, the costs of zero-emission technologies have fallen so dramatically that the estimated cost of achieving net zero emissions in 2050 is the same as the estimate in 2008 of achieving just an 80 per cent reduction within the same timeframe.[16]

Many technologies will experience a tipping point, where the cost of clean technology falls to such a degree that market dynamics will mainly drive developments and the role of policy will be to secure predictable framework conditions. This tipping point will come sooner if carbon pricing is applied in the form of taxes or an emissions trading system. When we pass these tipping points, things will move very quickly, but targeted and effective policies will be needed.

This dynamic has the greatest impact when climate policy is long-term and credible. When politicians set long-term climate targets ,reinforced with short term policies , it sends a clear signal to the market to invest in zero-emission technology.

Three examples of technologies where we see this development:

- Support for renewable energy at an early stage has driven down costs for renewable technology and made it easier and cheaper to cut emissions in the power sector. Now the power market and carbon pricing can drive the decarbonisation of the power sector without the need for subsidies for new production to a large extent. However, in order to achieve a sufficient speed of transition, strengthened carbon pricing is needed

- Political support for electric transport has driven down the cost of batteries. Consequently, the total cost of an electric car is now lower than the equivalent petrol/diesel car in many parts of the world. The decarbonisation of passenger cars will soon be driven by market forces, and the role of policy will be to ensure that framework conditions and infrastructure are in place quickly enough

- Political support for hydrogen production is driving down the unit cost of electrolysers and making it easier and cheaper to reduce emissions in industry. In the long term, this could also be market driven.

The dynamic is expected to be at its most powerful when the technology can be mass-produced. Better predictability about future developments will encourage industrial players to build factories and global, efficient supply chains. The positive spiral between policy and technology is also found in more complex technologies such as nuclear power, and carbon capture and storage. Here, costs are driven down by increased volume as a result of political decisions, more standardisation and the transfer of 'best practice'.

The EU has high ambitions for a rapid transition

The most ambitious and far-reaching climate policy is found in the EU. In December 2019, the President of the European Commission, Ursula von der Leyen, announced the European Green Deal, which is both a strategy for growth and a cross-sectoral plan for making Europe climate neutral by 2050. The overarching goal of the European Green Deal is the goal of zero greenhouse gas emissions and zero pollution by 2050. In June 2021, the EU passed its first climate law. Here the target of a net 55 per cent reduction in emissions by 2030 and of net zero emissions by 2050 with an associated carbon budget was enacted in law.[17]

As part of the European Green Deal, the EU aims to achieve a number of strategic goals. The focus is on the need to reduce greenhouse gas emissions. However, sustainable development provisions will also be entailed, with a view to halting the loss of biodiversity and preserving nature to a greater extent than today. Creating new and secure jobs and reducing the need to import energy are also important goals.

To achieve these goals, power production needs to be emission-free, and renewable power must be used in sectors where oil, coal and gas have previously been dominant. In addition, Europe's energy system will need to be more flexible and efficient. European industry will cut emissions and become more resource efficient. The buildings sector will be renovated and will reduce energy consumption. Meanwhile, products will have a longer lifetime and be recycled more efficiently. Agriculture will become more climate- and environment-friendly, and land use will be more considerate of nature.[18]

The European Green Deal is a roadmap for the EU to achieve several strategic targets, such as reduce emissions, create jobs and growth, reduce external energy dependency and focus on sustainability

'Fit for 55'

Ambitious climate targets need to be followed up with robust measures if they are to be credible. On 14 July, the European Commission launched 'Fit for 55', which is a comprehensive package of legislative initiatives that provides a policy framework for the EU to meet the steeper targets for a net 55 per cent reduction in emissions by 2030 and net zero emissions by 2050. The 'Fit for 55' package is the EU's main tool for following up and securing agreement on the 2030 and 2050 climate targets in the form of regulation. The package consists of twelve legislative proposals, two thirds of which are updates or revisions of existing legislation. The Council of the European Union and the European Parliament are set to negotiate these proposals in the coming months before the legislations can enter into force.[19]

Carbon pricing

The central role of carbon pricing in EU climate policy is continued and reinforced in the package. The proposed revision of the EU Emissions Trading Scheme (ETS) must balance a number of considerations, including predictability and stability for the market participants, the effort sharing between member states and sectors, and the risk of carbon leakage.

Every year, the total amount of available allowances (the cap) in the EU ETS is reduced. Central to the proposed revision is the increase of the overall ambition by lowering the cap annually*. In addition, the European Commission proposes a one-off reduction of the overall cap. To ensure balance in the market, it is proposed that the current set-up in the Market Stability Reserve (MSR) mechanism is continued with some modifications. In sum, the proposal from the European Commission will give a 61 per cent reduction in emissions before 2030 compared with 2005 for the sectors included in the EU ETS.

The European Commission wants new sectors to be covered by carbon pricing in the long term, and to strengthen the existing trading system. In the revision, shipping will be included in the current ETS. More controversial is the European Commission's proposal to introduce a separate emissions trading system for the transport and heating sectors. These sectors are not covered by the current ETS, and finding solutions to cut emissions in these sectors has so far been a national responsibility. The European Commission proposes that these sectors be covered by separate emissions trading systems as from 2026, and the design will be similar to the existing system in addition to still being a national responsibility.

Carbon Border Adjustment Mechanism

One of the most discussed proposals in the 'Fit for 55' package is the introduction of the Carbon Border Adjustment Mechanism (CBAM**). Higher carbon prices will mean that parts of European industry will be at a competitive disadvantage compared to businesses in countries without carbon pricing. This can either be in the form production processes that emit significant emissions, or energy-intensive processes that face rising power prices due to the higher carbon prices, or a combination of these two things.

Under the CBAM, a fee is levied on goods produced in regions without carbon pricing before being sold in Europe in order to offset the competitive advantage. This will enable European industry to remain competitive despite rising carbon prices. The CBAM will initially cover electricity, cement, fertilisers, aluminium and steel.

* Current legislation reduces the emission cap with a linear reduction factor at 2.2 per cent annually. It is now proposed that the linear reduction factor should increase to 4.2 per cent.

** CBAM = Carbon Border Adjustment Mechanism

The goal with the CBAM is to both avoid carbon leakage and to put pressure on the countries that trade with the EU to introduce more ambitious climate policy.

Such a mechanism is associated with a number of challenges. To avoid trade disputes, it must comply with the rules of the World Trade Organization (WTO). Although the CBAM ensures that all goods in the European market are covered by carbon pricing, the industry sector has been concerned that it could lose market shares in other markets. If the CBAM is fully implemented, it is likely that today's scheme with free allowances is gradually phased out, to be in compliance with the WTO.

Other directives and regulations

Carbon pricing is complemented with a number of other legislative proposals aimed at accelerating the transition and technological development, such as a strengthening of the effort sharing regulation that sets domestic climate targets for sectors outside of the ETS. The European Commission has proposed to increase the climate target from these sectors to 40 per cent by 2030 compared with 2005, compared to today's target of 30 per cent. The European Commission's proposal for a revised renewables directive sets a new binding target in Europe for a 40 per cent share of renewable energy by 2030. This is twice the current level, and significantly higher than the target of 32 per cent renewables in the energy mix in 2030 that was agreed in the last revision of the Renewables Directive in 2018.

The European Commission proposes to increase the share of renewable energy in industry by 1.1 per cent per year until 2030. It further proposes a target of 49 per cent of renewable energy in buildings by 2030, and a sub-target of 50 per cent of renewable energy in hydrogen production in industry. The Energy Efficiency Directive is also being revised with a new binding goal to reduce energy consumption in the EU by 39 per cent by 2030. For the transport sector, the European Commission has proposed reducing emissions from new car sales by 55 per cent by 2030 and 100 per cent by 2035.

The United States rejoins the Paris Agreement under Biden

Climate policy has long been part of the American political debate, even so, getting climate policy decisions through at the federal level has proved difficult. For example, the United States never ratified the Kyoto Protocol, and several attempts to introduce climate legislation have failed to make it past Congress.

Under President Obama, the United States took a leading role in international climate negotiations and was a key player in negotiating the Paris Agreement. However, on his home turf, Obama normally had to resort to executive orders to introduce climate measures. The United States' incorporation into the Paris Agreement was also the result of an executive order. The problem with these executive orders is that a new president can reverse them without going through Congress. Much of Obama's climate agenda was consequently reversed by the Trump administration.

Climate policy was a core component in Biden's political platform in last year's presidential election campaign. He launched a number of specific measures related to the green shift, with a focus on reducing emissions in both the energy and transport sectors, as well as creating new 'sustainable' jobs. Since the election, Biden has signed a number of executive orders, one of which was to re-join the Paris Agreement. An executive order was also used to intensify the United States' ambition by pledging net zero emissions by 2050 and a 50 per cent reduction in emissions by 2030 compared to 2005.[20]

Biden's 'Green Deal' or 'American Jobs Plan' is now ready to go before Congress after being passed in the Senate on 10 August this year. The package is a comprehensive USD 1 000 billion infrastructure plan, of which USD 550 billion is new funds. Originally, the package included USD 2 250 billion worth of measures, but this was reduced due to political disagreement. The plan covers major investments in roads, bridges, railways, water pipes and broadband. It also includes green investment, such as USD 73 billion to renew the electric grid, USD 17 billion for port improvements that will enable offshore wind expansion, USD 9.5 billion to reduce the cost of clean hydrogen, and USD 7.5 billion for electric vehicle infrastructure such as charging stations. The package will now be considered in the House of Representatives, where the Democrats can pass it with a simple majority.[21]

The individual states play a key role in American climate policy, both through the implementation of federal policy and their own climate targets, measures and regulations. As of today, 24 states have dedicated climate targets. Several states have also introduced emissions trading systems to regulate emissions. The Regional Greenhouse Gas Initiative (RGGI) is a carbon market for reducing emissions in the power sector, covering 11 states on the northeast coast. California has its own trading system, which is linked to Quebec in Canada.[22]

Independent of whether the climate policy relies on a carbon price or other instruments , it is key that the US is back in the driving seat on global climate policy. It will be important to follow the dynamics between the US, EU and China during this year's climate summit, COP26, to see whether the three blocks are able to drive the climate negotiations forward.

China aiming for carbon neutrality by 2060

China has experienced substantial industrialisation and vast economic growth in the last 30 years. However, this has been at the expense of the environment and the climate. China accounted for 28 per cent of the global CO_2 emissions in 2019. The energy sector (power and heating) accounted for just over 40 per cent of national CO_2 emissions, followed by industry with about 31 per cent. Power production is dominated by coal, but even so renewable sources produce almost 30 pre cent as a consequence of a large-scale expansion of renewable power production, with hydropower accounting for just over half the power production.[23]

The 12th five-year plan (2011-2015) marked the introduction of a clear climate policy on the main political agenda. This was followed up in the 13th five-year plan (2016-2020) where, for

2020 was the fifth year that investments in renewable energy are greater than investments in coal in China

the first time, green growth was described as one of the most important priority areas. The country signed the Paris Agreement in 2016 and surprised the world in the autumn of 2020 when it announced its goal of carbon neutrality by 2060 and a target of around 40 per cent non-fossil energy in the total consumption by 2030. In September 2021, president Xi Jinping also announced that China will stop financing coal power plants abroad, which would affect almost 60% of all coal plants planned outside of China and India.[24]

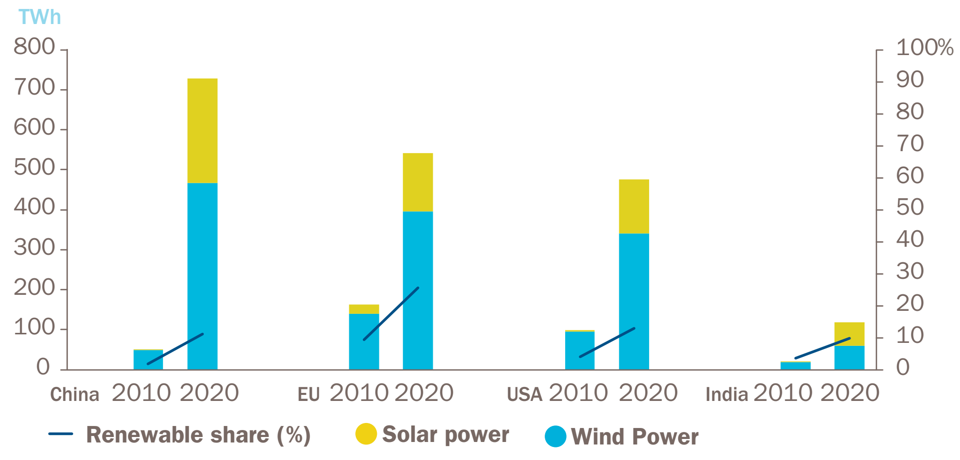
Climate policy is also a core part of the most recent five-year plan (2021-2025), but there is still no definitive cap for greenhouse gas emissions. Its sharply increasing GDP and energy-intensive economy means that China can achieve the goals in its five-year plan and still increase emissions by one to two per cent per year. In 2020, new coal power plants with a capacity of 38 GW were completed in China, at a rate of roughly one a week. The increase in new coal capacity in China is almost three times as much as the rest of the world combined.[25]

China is a world leader in renewable energy, both in terms of production and use, particularly in relation to solar and wind power. Production capacity from wind power is now 280 GW, which is 25 per cent more than in the whole of Europe. Only 9 GW comes from offshore wind (Europe has 25 GW), but this is now a priority.[26]

The introduction of a national emissions trading system was agreed at the highest political level in 2015, and this was one of the country's Nationally Determined Contributions (NDCs*) under the Paris Agreement. After this, carbon markets were gradually introduced in some states in pilot schemes. The pilot schemes were merged to one national emissions trading system which was officially launched in July 2021. The trading system is estimated to cover more than 4 billion tonnes of CO_2, corresponding to 40 per cent of national carbon emissions, and there are plans to further expand its reach in the future. China's national emissions trading system will be the world's largest and is expected to be one of the most important instruments for realising the country's climate ambition both in the short and long term, together with an increase in the share of renewables and a reduction in the use and expansion of coal power.[27]

Despite several positive signs from China, its climate ambitions need to be dramatically strengthened to bring it in line with what is needed to limit global warming to 1.5°C.

2 Wind and solar power production in China, USA, EU and India (TWh) and renewable share of total power production (%)[32]



India investing in renewable energy and electric cars, but climate ambitions are unclear

India has experienced strong economic growth and a rapidly growing population in recent decades. This has also led to a sharp increase in the demand for energy. Energy consumption has doubled since the year 2000, and India is currently the third largest consumer of energy in the world. Since coal, oil and biomass meet 80 per cent of the demand, greenhouse gas emissions and local pollution have increased.[28]

In 2020, it is estimated that 97 per cent of the Indian population is connected to the power grid, which means that over 900 million people have been given access to electricity since 2000. India's goal in the Paris Agreement is to reduce the intensity of emissions in the economy by 33-35 per cent by 2030 compared to the 2005 level, and to achieve a 40 per cent share of non-fossil power production by 2030.[29]

Coal in India is a complex picture. 2020 is the fifth year that investment in renewable energy is higher than investment in coal. More than USD 10 billion is still invested in coal each year, but according to the IEA, there has been a sharp decline in new investment decisions since 2016, which may indicate that investment will be considerably reduced in the years ahead. India has the fifth largest coal reserves in the world, but is nevertheless a major importer of coal, with as much as 33 per cent of coal demand being met from imports.[30]

The Indian authorities have implemented a number of climate policy measures, both at a local and national level, to meet the targets set in the Paris Agreement. Between 2015 and 2019, investment in renewable energy grew by 60 per cent, and is now USD 18 billion annually. A support system with auctions for renewable power projects has reinforced this development. A number of legislations have also been introduced for energy-efficient buildings, and they have introduced energy efficiency standards for cars. Increased use of biofuels in the transport sector is also a target. One policy measure that has had a major impact is the phase-out of incandescent lightbulbs, which have been replaced with LED bulbs. The result is a 54 TWh saving in energy consumption.[31]

*Nationally Determined Contributions, countries' commitment under the Paris Agreement

The opportunity to create new, green jobs is highlighted by many politicians as a central part of the green agenda.

A more complex green agenda

As society starts to better understand the impact of global warming, many countries are setting ever higher targets to reduce greenhouse gas emissions. The increasingly ambitious climate policies are progressively impacting more parts of society and the economy.

Many sectors will need to cut emissions, and the transition to renewable power production will have to pick up pace. As a more comprehensive approach is taken to climate policy, other political objectives must also be considered, such as employment and traditional environmental protection. Furthermore, the distributional effects of climate policy are becoming more salient and apparent. A just transition and possible forms of compensation and burden sharing are therefore becoming more and more important. This is reflected in several important political processes today.[33]

Environmental protection has traditionally had a strong position in the EUs regulations, and this is strengthened through the European Green Deal. Regulations tied to pollution is strengthened, while biodiversity and the circular economy are also put forward. Likewise, the EU taxonomy supports the trend where climate – still the main goal behind the European Green deal – complements environmental considerations in financial reporting requirements.

When it comes to biodiversity, the EU emphasises both preservation and restauration of nature and species. The target for 2030 is to protect 30 per cent of the EUs land and sea area with binding environmental targets and plans for biodiversity. This can strengthen the requirements for the construction and operations on green projects and increase the requirements for documentation and thereby impact the rollout of different green technologies. At the same time will requirements for protection of land and sea areas affect different technologies in different ways.

The Circular Economy has a special place in the EUs Green Deal. Only 10 per cent of EUs demand for materials comes from recycling today. Stricter demands for surveillance and documentation regarding the footprints and origination of different materials are expected. For clean technologies, this can mean stricter demands for documentation of materials, life cycle analyses, reuse, and recycling in general. This can also lead to that the already strong trend regarding documentation and certification of the use of renewable energy is further strengthened globally and in Europe.

Within pollution, it expected that the existing regulations regarding air, water, and land pollution are strengthened. Additionally, stricter demands for reduced visual pollution and noise pollution are expected. Strengthened regulations regarding pollution is expected to lead to stricter surveillance and transparency. This can affect different technologies in different ways and could increase the costs related to polluting.

This focus on environment in a broader sense is also reflected outside of EU, in international and national discussions. The green agenda has overall become more complex.

The energy transition will require large investments in the production, storage and distribution of renewable energy, in addition to finding new ways of using energy more efficiently. This will create jobs.

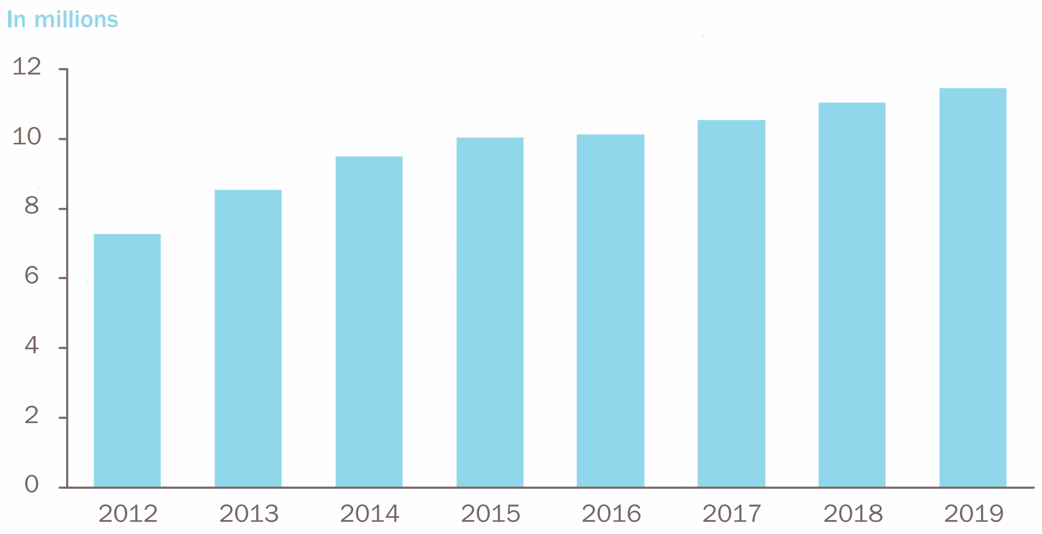
2

Employment growth in the renewable energy industry

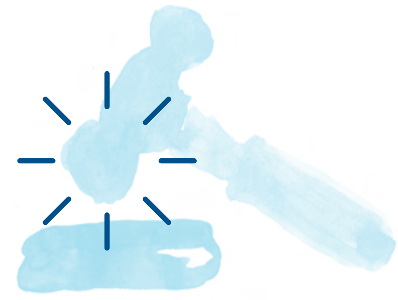
The energy transition will require large investments in the production, storage and distribution of renewable energy, in addition to finding new ways of using energy more efficiently. This will create jobs.

The possibility for creating new, green jobs is emphasised by a lot of politician as a central part of the green agenda. Joe Biden promised to create 10 million green jobs during his presidential campaign. EUs Green Deal highlights the possibility for new jobs. Both companies and governments want lasting industrial effects of the large-scale investments they are facing. The pandemic with subsequent stimulus packages has supported this development trend, and we see an increased investment in industrial development globally.[34]

3 Renewable energy jobs (millions)[35]



Since 2012, the number of jobs in renewable energy has increased by almost 60 per cent, and almost tripled in solar energy. If the global energy transition set out in the Paris Agreement are realized, the number of jobs in renewable energy will have quadrupled by 2050. On top of this, there will be jobs in the distribution and storage of energy, and energy efficiency. IRENA estimates that If we are to meet the climate targets, the number of energy transition-related jobs will increase by around 30 million towards 2050. Most of the renewable jobs, around 60 per cent, are expected to be in Asia.[36] In order to get to net zero emissions, the IEA estimates that 16 million jobs will be needed in renewable power, energy efficiency and low-emission technologies no later than 2030.[37]



To challenge climate and sustainability ambitions in courts has been a growing trend in recent years

A comprehensive and powerful climate policy will lead to changes for many people, and a 'just transition' has increasingly gained focus in the last years. This received a special place in the establishing of the European Green Deal and gained more importance during the Covid-19 pandemic. The transition in the energy markets gives opportunities and a need for more green business and industrial development.

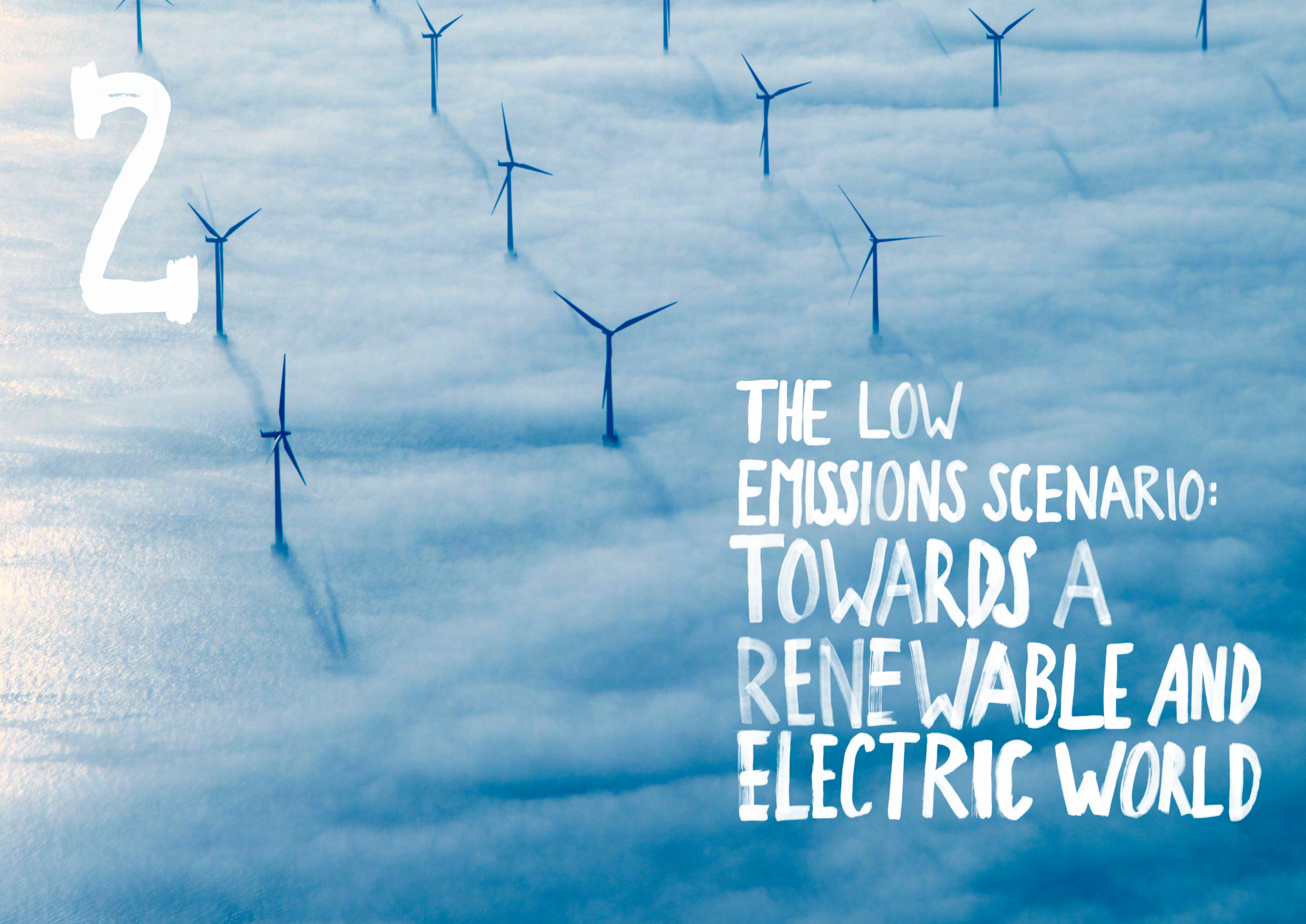
Increased pressure from legal and financial markets

Taking climate and sustainability policy to the courts has been a growing trend in recent years. In 2020, a total of 1,500 court cases involving global warming were held across 38 different countries, the majority of which were in the United States. One of the verdicts that has received the most attention was in a court in the Netherlands, which concluded that the country's climate policy is neither ambitious enough nor specific enough. Similar rulings have been made in the German Constitutional Court and in an administrative court in Paris. In Australia, a court ruled that climate change will pose major challenges to the next generation in the form of heat waves and wildfires. The rulings reflect how the evidence of global warming is now so strong that it holds up in court, in addition to the fact that countries have pledged to limit global warming through the Paris Agreement.[38]

It is not just nations that are being legally compelled to improve their climate targets. In May 2021, a Dutch court ruled that Shell's sustainability efforts were insufficient and needed to be more detailed. Shell was ordered to reduce the 2019 level of emissions by 45 per cent by 2030, including its indirect emissions from sold oil and gas, with the court arguing that this was in line with the Paris Agreement. The ruling is based on the notion that insufficient climate action is a breach of both the European Convention on Human Rights and Dutch civil law. The verdict stated that there has been broad international consensus since 2012 that non-state actors also have a responsibility to undertake climate action and that Shell's emissions were at the same level as many national states.[39]

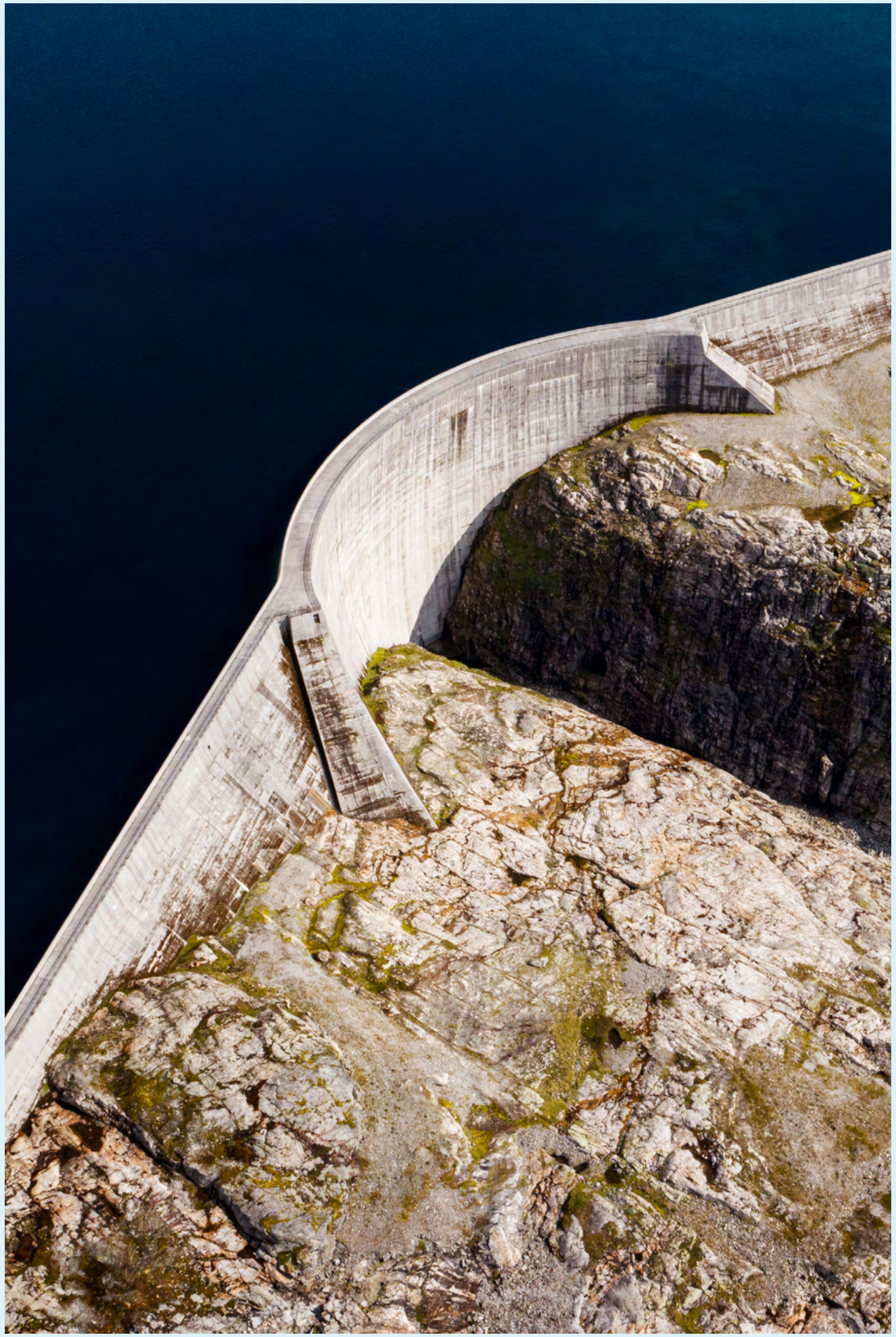
At the same time, the pressure increases in the financial markets. As an example, EU has taken the leading role within sustainable finance and is currently introducing comprehensive rules for sustainability reporting based on the EU taxonomy. The reporting requirements cover around 50 000 companies and is expected to increase the pressure on companies from investors, insurance companies, banks, financial auditors, and owners.[40]

It is too early to tell how this move towards increased financial reporting and risk of legal claims will impact on national policy developments and companies' actions. However, there is reason to believe that we will see more examples of organisations taking businesses to court and of human rights being cited as a legal basis for action against companies. This can have both political and commercial implications, also taking into account the burden companies face in such conflicts.



2

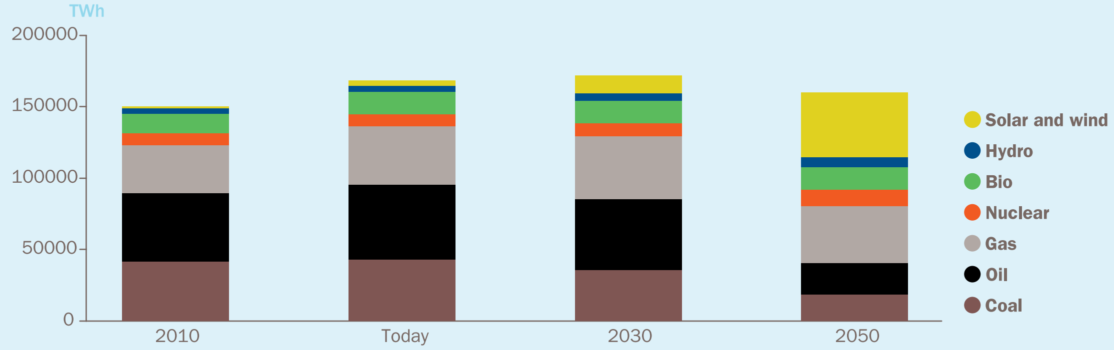
THE LOW EMISSIONS SCENARIO: TOWARDS A RENEWABLE AND ELECTRIC WORLD



Global hydropower capacity will grow by approximately 1.5 per cent yearly up to 2050.

4

Primary energy demand by energy source 2010-2050. The Low Emissions Scenario have the same level of primary energy demand in 2050 as today, but with a different mix (TWh)*.



Statkraft's Low Emissions Scenario: towards a renewable and electric world

In this chapter we present our Low Emissions Scenario. The scenario represents a world where increased climate policy and falling technology costs reinforce each other and create a dynamic that will drive the energy transition forward. The scenario does not start with a given climate target but is instead our view of what the world will achieve if the existing momentum for climate change is continued.

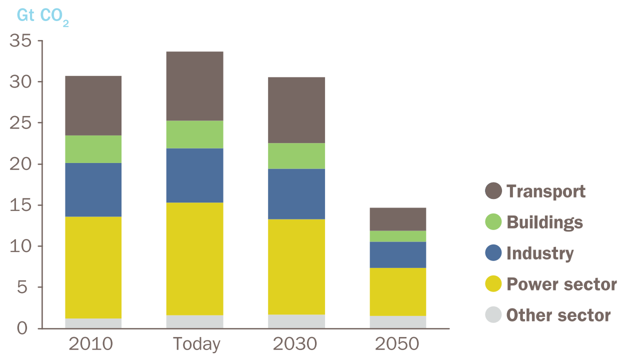
In the power sector, it has become apparent that we are in the middle of a renewables revolution: Solar and wind power are winners in the global competition to supply the world with affordable, clean power. The cost level is the main reason why solar and wind power outcompete other technologies, in addition to their benefits to the climate. Tougher climate targets add to the pressure in industry, transport and buildings to cut emissions, and with a more renewable power sector, direct use of electricity will be a cost-effective climate measure for these sectors. Society is being electrified. Direct use of clean renewable power means more affordable and more efficient energy consumption in transport, heating and industrial processes. It reduces both local pollution and global greenhouse gas emissions.

For sectors where direct use of electricity is a challenge, one of the few solutions to cut emissions is to use renewable energy indirectly through emission-free hydrogen. Direct and indirect use of renewable power links the sectors more closely through so-called sector coupling.

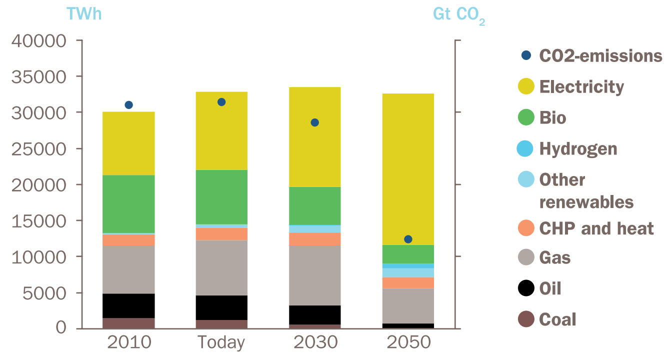
Our analyses show that reducing emissions in the power sector first, is a good strategy. However, we cannot wait until the global power sector is completely emission-free to electrify cars or develop the hydrogen industry. It takes time to build value chains and infrastructure. In addition, electric car charging and hydrogen production can provide crucial flexibility for the power system, which again could support further investment in wind and solar power. Clean hydrogen can also play a key role in cutting the last emissions in the power sector.

* 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.

5 Global energy-related CO_2 emissions by sector ($Gt\ CO_2$).



6 Global energy demand for buildings by energy carrier (TWh) (left) and total emissions for buildings ($GtCO_2$) (right).



Electrification is the biggest contributor to emission cuts

There are various measures to reduce greenhouse gas emissions from energy use. Energy efficiency, use of hydrogen, bio, and carbon capture and storage are all important technologies for meeting the target set in the Paris Agreement of well below 2°C global warming. In the Low Emissions Scenario, decarbonisation mainly takes place in the form of renewable power and electrification. We see that the use of electricity has four major advantages:

1. Electricity reduces local emissions. This means that the air quality and the environment in towns and cities will be significantly better if, for example, the transport sector is electrified.

2. Saved energy is the most environment-friendly type of energy. Using electricity instead of fossil fuels is often more energy-efficient. A heat pump only needs around one third of the energy of a gas boiler to provide the same energy service. This also applies to electric cars, which only need around one third of the energy of fossil cars for the same distance.

3. The use of electricity links the different sectors, so-called sector coupling. This is a major factor in the efforts to solve the need for flexibility in the power system.

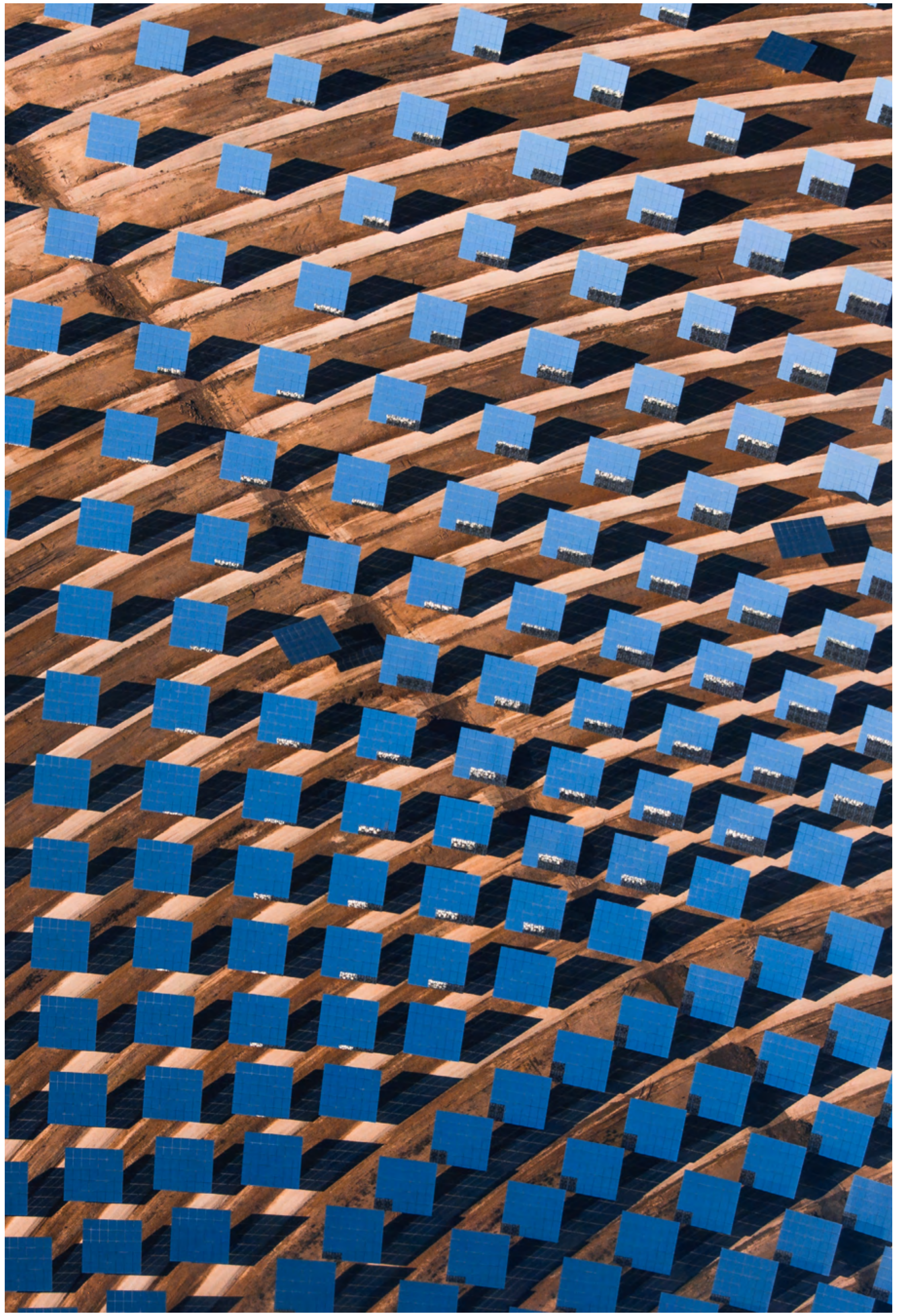
4. If the electricity comes from renewable sources, the emissions will be zero. Electricity from a gradually more renewable power sector is the key to decarbonisation in the Low Emissions Scenario.

Emission reductions in buildings through electrification and energy efficiency

The building sector's emissions, mainly from room heating and cooking, account for about ten percent of global energy-related CO_2 emissions. Fossil gas, in particular, is widely used for heating in many parts of the world. Traditional biomass is typically used in poorer countries (e.g. wood burning or open fire cooking). Sustainable biomass is considered to be emission-free, even so, cooking and heating with traditional biofuels is problematic with regard to the local environment and air quality. In the Low Emissions Scenario, the use of electricity in the building sector is increasing, while the use of fossil fuels and traditional bioenergy is in decline.

Electricity can be used in different ways to generate heat. Historically, electricity has been used directly via electric heaters or electric boilers. Today, heat pumps are becoming increasingly common. Heat pumps utilise the heat from the air as well as the power they consume, and consequently generate around three times as much heat as they use in electricity.* The large energy gains and emission cuts are leading to a silent heat pump revolution in Europe. The most extensive transition to electric heating is expected to take place in Europe due to its high gas prices, high climate ambitions and relatively cold climate, but this trend is also being seen globally. In France, the heat pump stock has increased with over 2 million units the last ten

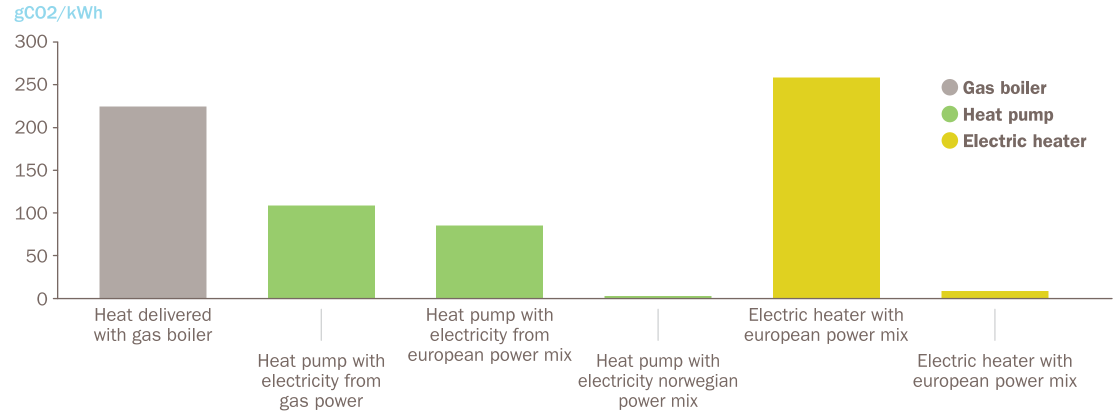
* Heat pump efficiency depends on the temperature of the heat that the pump extracts from the environment and will range from 200-500 per cent. In Canada, heat pumps that are designed for cold climates have an efficiency of 200 per cent with temperatures lower than -20°C.



In the Low Emissions Scenario, the capacity in the global power sector will increase three-fold between now and 2050.

8 CO_2-emissions from different heating solutions (gCO_2/kWh)*

* Heat pump COP assumed to be 300, efficiency assumed for electric heater, gas boiler and gas turbine is 99%, 90%, 62 % (LHV) respectively. It is assumed emission intensity of 256 gCO_2/kWh for European power mix and 8 gCO_2/kWh for the Norwegian power mix.



years. 400 000 heat pump units were sold in 2020, twice as high as five years ago[41]. In the Low Emissions Scenario, 50 per cent of the heating demand will be met by heat pumps in 2050 globally.

The cleaner the electricity a heat pump uses, the less CO_2 will be emitted, but heat pumps can be very helpful in reducing emissions even when the power comes from fossil sources because of the high efficiency. If the electricity in a heat pump comes from a gas power plant with 60 per cent efficiency, the emissions will be more than halved compared to a traditional gas boiler with 90 per cent efficiency.
This reduction is even greater if you replace an electric heater with European power mix. Although the greatest reduction in emissions from heat pumps is seen when the pumps replace other heating from fossil fuel boilers, heat pumps have a high energy efficiency rate, which leads to energy savings.
Energy efficiency in buildings, both in the building mass, in appliances and with the use of heat pumps, is an important contribution to lower greenhouse gas emissions.

Energy savings can also be made in relation to cooking. In many countries, gas remains the standard source of energy in cookers. A shift to induction cookers will reduce emissions, increase efficiency, improve safety and provide a better indoor climate. In poor areas, more people will switch from traditional biomass in cooking to more energy-efficient and safe sources, such as electricity and fossil gases. In order for the world to get to net zero emissions, also fossil gases need to be phased out.

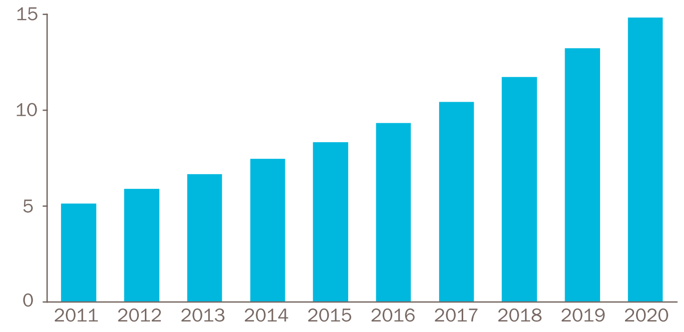
Emission reductions in transport through electricity and hydrogen

The transport sector accounts for almost 25 per cent of today's energy-related CO_2 emissions, and 75 per cent of this is from road transport. The main energy source in the transport sector is oil (Figure 9).

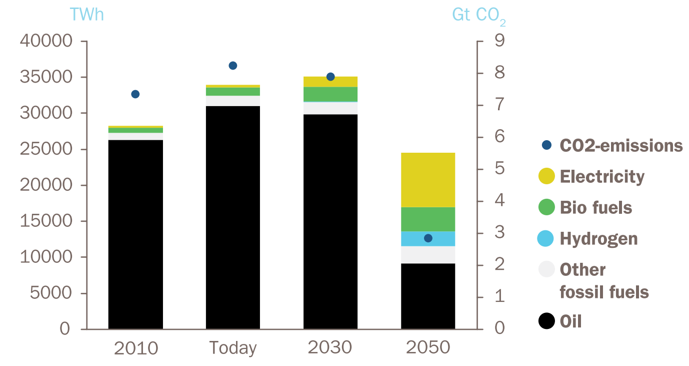
Electric vehicles are rapidly making their mark on the transport sector, and several car manufacturers have set high targets for future electric car sales. Globally, 2020 was a very good year for electric cars, and this has continued into 2021. Despite the COVID-19 pandemic, sales of fully electric cars increased by 40 per cent in 2020, even though total car sales fell. Including plug-in hybrids, electric cars accounted for 4 per cent of global car sales.
In the first quarter of 2021, global electric car sales increased by 154 per cent, while total car sales increased by 21 per cent. New models from car manufacturers, together with a growing number of political instruments, are strong drivers of the growth. More and more manufacturers are setting ambitious targets for electric car sales:

- Ford is aiming for a 40 per cent market share in electric cars by 2030 and will invest USD 30 billion by 2025. Ford plans to be selling only fully electric cars in Europe by 2030.
- Volvo is aiming to only sell electric cars as from 2030.
- Volkswagen has a target of 70 per cent electric car sales in Europe and 50 per cent in China and the United States by 2030.
- Mercedes' goal is to be fully electric by 2030. Half of their models will already be electric by 2025.

7 Total heat pump stock in 21 of EU's countries the last ten years (millions)[42]

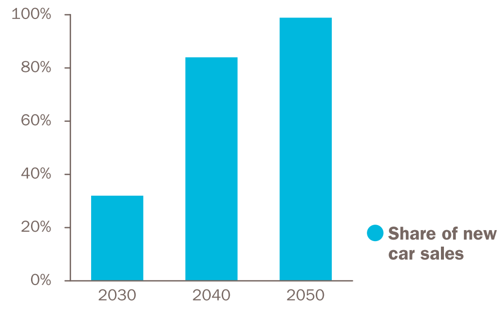


9 Global energy demand from the transport sector by energy carrier (TWh) (left) and total emissions for transport (Gt CO_2) (right)



In addition to car manufacturers offering a more varied assortment, the infrastructure is constantly improving, battery costs are falling, and support schemes are being introduced. China, Europe, and the US account for over 40 per cent of global passenger transport and a lot is happening. In Biden's infrastructure package, USD 174 billion of investment was announced in electric car subsidies and charging infrastructure, among other things.
The EU's 'Fit for 55' package proposes targets for electric car chargers per member state. Many European countries also have national targets, incentives and regulations to accelerate the transition to electric cars.[43] In Statkraft's Low Emissions Scenario, these trends are set to continue, and will lead to relatively quick electrification of the global passenger car fleet.

10 Emission-free share of new car sales globally

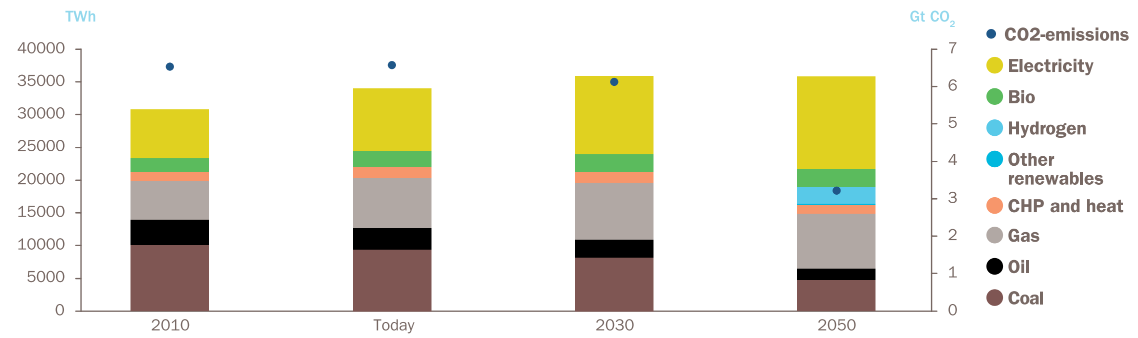


There are now more than 11 million electric cars in the world (fully electric and plug-in hybrids).[44] In some countries, the total cost of ownership of an electric car is already lower than that of a fossil car. This is expected to be the case in many parts of the world before 2030 and will further accelerate the growth of electric cars. As car manufacturers produce more electric cars, they will also reduce the number of fossil cars being produced.
We estimate that 40 per cent of new cars sold in 2030 will be electric, and that this will increase to almost 100 per cent and over 1.6 billion electric cars will be on the road by 2050.

An electric car only needs about a third of the energy of a petrol or diesel car. Energy demand from the transport sector will be reduced by around 30 per cent between 2030 and 2050 despite a growth in transport need.
Heavy transport, particularly large trucks that travel long distances, is more difficult to electrify due to the volume and weight limitation of the battery. However, trucks and buses that travel shorter distances can be electrified. Overall, we estimate that around half of new truck sales will be emission-free in 2050 (battery electric and hydrogen). Also, the shipping and aviation sector will be a challenge in terms of direct electrification.

Sustainable biofuels and hydrogen-based fuels will complement each other to decarbonize the transport sub-sectors that are hard to electrify. Short domestic flights may eventually be electrified, but this technology is not mature.
Car ferries and boats that serve short coastal routes can already be powered by battery.
For longer distances, ammonia produced from green hydrogen will be able to provide CO_2-free transport at sea. The International Maritime Organization (IMO) has a goal of reducing total greenhouse gas emissions by 50 per cent by 2050 compared to the 2008 level. In the Low Emissions Scenario, we assume that five per

11 Global energy demand from the industry sector by energy carrier (TWh) (left) and total emissions for industry (Gt CO2) (right)



cent of the energy consumption in maritime transport will be electricity by 2050, primarily as a result of battery-electric ferries on short routes. We also assume that around 12 per cent of the global energy consumption in the maritime sector will come from emission-free ammonia by 2050. In the Low Emissions Scenario, it is assumed that the IMO targets can be met through a combination of alternative fuels and more energy-efficient operation of vessels. However, the IMO targets must be further tightened if the world is to follow a 1.5°C pathway.

In 2050, transport emissions in the Low Emissions Scenario will be 70 per cent less than today. Passenger car transport will mainly be emission-free, and the remaining emissions will primarily be from long-distance transport between countries and continents, such as shipping, aviation, and heavy transport by road. If we are to meet the 1.5°C target, greater international cooperation and more ambitious emission cuts will be needed than those seen in the Low Emissions Scenario for the rest of the transport sector.

More renewable energy in industry

The industry sector is energy- and emissions-intensive. Total energy-related CO_2 emissions from industry account for 19 per cent of global energy-related emissions.* Parts of the industry sector are a challenge to electrify, especially thermal processes that require temperatures in excess of 500°C. The technology needed to electrify such processes is still in the development phase. Other emission-free alternatives to such processes are clean hydrogen, bioenergy and CCS.

About half of the heat used in industry can be categorised as low temperature, i.e. below 200°C. Such processes can be electrified using existing technology, which can be implemented across sectors. Heat pumps and electric boilers can replace thermal processes that are common-place in many industries. This equipment can be retrofitted to existing machinery, and hybrid systems can be installed. Electrification using heat pumps, where this is possible, will also improve efficiency. Introducing smart systems that are connected to heat can enable flexibility for parts of the industry energy demand.

In the Low Emissions Scenario, the energy consumption in the industry sector comes out flat, despite underlying growth. This is a result of energy efficiency gains, more efficient use of material and a high share of recycling. This, together with electrification, use of clean hydrogen, and some CCS, reduces the current energy-related CO_2 emissions by 51 per cent by 2050.

Electrification of industry will take time, and the Low Emissions Scenario assumes a gradual electrification up to 2050. By 2050, 40 per cent of the global energy demand in industry will be met by electricity. The EU will have made the most progress, with around 60 per cent electrification. Hydrogen, bioenergy and some fossil fuels with CCS will be used to meet the rest of the energy demand. In other parts of the world, such as India, China and the rest of Asia, fossil-based manufacturing capacity is still

* 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.

3

Circular economy and recycling steel in the European Union

Recycling is well established within metals, plastics, glass, and paper, and is an important measure in the decarbonisation of industry. Recycled plastic, for example, saves approximately 50-60 per cent in greenhouse gas emissions compared to normal plastic production. For sectors experiencing rapidly growing demand, there will not be a sufficient supply of scrap and waste for recycling alone to meet the demand. More efficient use of materials and reduced energy demand are therefore important for achieving a low-carbon, circular economy.[45]

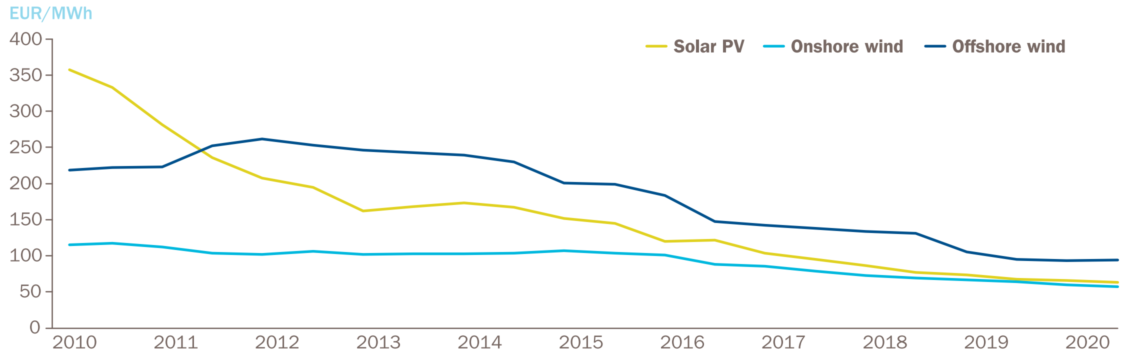
The steel industry is a good example. Recycled steel can be produced using emission-free power. Most recycled steel is currently produced using electric arc furnaces, and the entire process uses around 20-25 per cent of the energy used to produce primary steel. When recycled scrap metal is used for steel production, the most energy- and emission-intensive part of the production, which is the smelting and production of iron from iron ore, disappears.[46]

Steel is mainly used in buildings and in vehicles, both of which have a long life span. Together with a demand that has doubled since 2000, this means that recycling only meets a limited part of the steel demand even though recycling rates are high. Today, 85 per cent of the global steel consumption is recycled, which covers around a third of the global steel demand.[47]

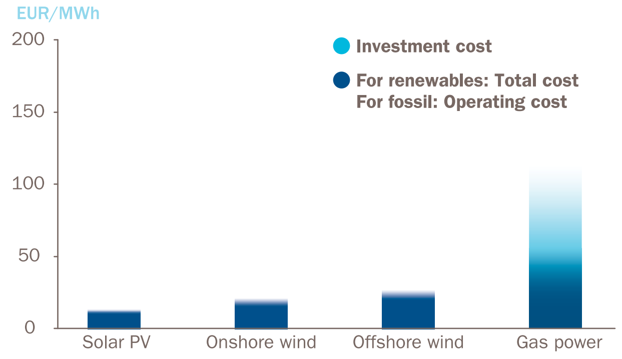
The EU's Circular Economy Action Plan includes sectors such as plastics, waste management, consumer electronics, textiles, transport, batteries, and biomass.
Its goal is that by 2030, only safe, circular, and sustainable products will be available in the European market. The EU has identified the circular economy as a strategic opportunity to, for instance, promote more efficient use of resources. The Circular Economy Action Plan also covers elements of trade policy. The EU wants to use access to the free market in Europe to promote circular rules of trade through the WTO and free trade agreements, and in so doing promote the concept of a circular economy, also globally. Products being sold in the EU are expected to comply with EU eco-design standards.[48]

12 LCOE* for different renewable technologies[50]

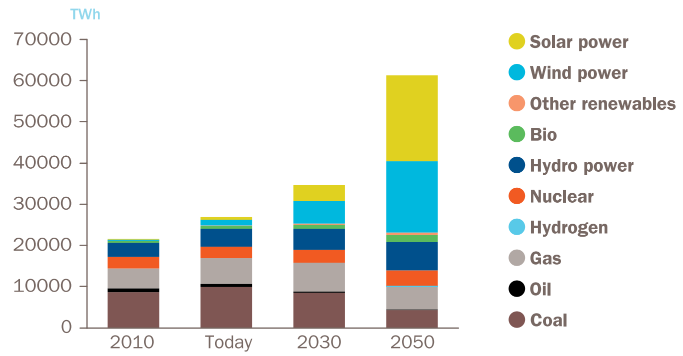
* Levelized cost of electricity



13 LCOE for different power producing technologies in Western-Europe in 2050



14 Power demand by energy carrier (TWh)



being built, and this has a lifespan of around 40 years. It is assumed that electrification and decarbonization of industry will take longer in these countries.

The power sector is becoming cleaner: solar and wind power are outcompeting coal and gas

All renewable technologies are growing
All renewable technologies - solar power, wind power and hydropower - are needed to meet the climate targets, and will grow considerably up to 2050 in the Low Emissions Scenario.

Huge cost reductions have been seen in solar and wind power in the last ten years.
Solar power costs have fallen about 85 per cent since 2010. The increasingly efficient production of solar PV panels and the lower installation costs have been the key drivers. Furthermore, advances in materials technology mean that solar PV panels are more efficient, which also reduces costs.

For onshore wind power, the costs have not fallen quite as quickly, but they have nevertheless been halved over the last 10 years. Here, the cost reduction is mainly driven by large wind turbines, which increase production levels and reduce production costs. The capacity of a modern wind turbine in 2000 was about 1 MW, whereas new wind turbines today have 3-4 MW, and by 2050 this could reach 10 MW. The blades and turbines on a 10 MW turbine are so large that segmentation in needed. This is a technique that allows the blades and the tower to be transported in parts and mounted together at the final destination. Large turbines increase production volumes and reduce costs. The turbines in offshore wind power plants can potentially be even bigger as they are not limited by the same logistical challenges.
For example, in the offshore wind project ‘Dogger Bank C’, which is scheduled for completion in 2026, there are plans to install turbines with a capacity of 14 MW.[49]

More digitisation, better preventive maintenance methods and better control and management systems can further reduce costs for all renewable technologies.

In the Low Emissions Scenario, the capacity in the global power sector will increase three-fold between now and 2050. This entire increase, and more besides, will be covered by renewable energy. This is primarily driven by the fall in costs for solar and wind power up to 2050.
Our analyses show that it is already cheaper to install renewable power production when new capacity is to be built. Solar and wind power are also outcompeting existing coal and gas power plants in more and more places around the world. Meaning, it will be cheaper to build new renewable capacity than to pay for coal and gas to fuel existing fossil power plants.

This is creating a powerful dynamic around the world, where fossil energy is being outcompeted by renewable energy. Between 2008 and 2018, installed solar and wind capacity grew by 42 per cent and 17 per cent annually, respectively.
In the years up to 2050, solar power capacity increases on average by 10 per cent per year to almost 13,000 GW, while onshore wind power increases by over 5 per cent per year to 3,500 GW and offshore wind increases by 13 per cent per year to 1,400 GW. Hydropower is the largest renewable power source today, with 1,300 GW of installed capacity globally, and will grow by around 1.5 per cent annually over the period. This shows clearly that the world is in the middle of a renewable revolution.

Solar power is not only low cost, it is also flexible in terms of location and is fast and easy to build compared to other technologies. As in last year’s analysis, solar power production will surpass wind power, hydropower, coal power and gas power, and will be the largest source of power from around 2035.

Onshore wind is the most affordable source of power in many parts of the world. The seasonal profile fits well in Europe, with a lot of wind in the winter when there is less sun. Wind power therefore complements solar power well.
The Low Emissions Scenario assumes a strong growth of onshore wind power around the world; without onshore wind power it will be impossible to meet ambitious climate targets.

Compared to onshore wind power, offshore wind is in general more expensive. Offshore wind has some advantages such as more even production and that wind turbines can be located relatively close to high consumption areas along the coast. In particular, floating offshore wind will be a significant contributor to the power systems in Japan, South Korea and parts of the United States, where populations are dense, available land is scarce and sea areas are often unsuitable for bottom-fixed installations. Large areas of Europe have good wind conditions that are well suited for bottom-fixed technology. Installations with a fixed bottom are therefore expected to dominate, although floating offshore wind is also expected.

Onshore wind is the most affordable source of power in many parts of the world. The seasonal profile fits well in Europe, with a lot of wind in the winter when there is less sun.

4

Power grid in the North Sea

Offshore wind is one of the fastest growing energy sources in Europe after solar power and onshore wind. More than 3 GW of capacity has been developed annually in recent years, and this will increase to well over 10 GW per year by 2030. The expansion is driven by the ambitious targets set by the EU and national authorities, which consider offshore wind to be essential for being able to reduce emissions. As of 2020, around 25 GW of capacity has been installed in Europe, and by 2030, the EU and the UK will have 60 GW and 40 GW in operation respectively. The EU has a target of 300 GW of offshore wind by 2050.[51]

High and stable wind speeds in the North Sea of 9-11 m/s average wind, and capacity factors that can reach over 50 per cent, will make offshore wind a great contributor to balancing the power markets. Production can be built close to the demand geographically, with the many large cities along the coast of Europe. Offshore wind plants do not take up space on land and are often placed out of sight, which can reduce the potential for conflicts.

Expanding offshore wind capacity to more than 300 GW in Europe by 2050 could present major challenges in terms of coordination and grid expansion. The power must be efficiently incorporated into the onshore grids, and it must be possible to transport it across the continent to inland areas of consumption. A large-scale expansion of offshore wind therefore requires a similar investment in grid expansion in Europe, and the EU has launched plans to address this.[52]

Today's offshore wind project is connected to a unique point on land. Increased volumes will mean a greater need for coordination of the wind farms and between the countries, and separate offshore grids have been proposed as a possible solution. An offshore grid that connects wind power projects to the same landing points, but also to different countries, could therefore be part of the solution. Denmark is already planning for this with two artificial energy islands that will collect power from several wind farms before landing. Other initiatives include a possible power cable between the UK and the Netherlands, where wind projects can connect and sell power to both markets.[53]

Designing such a market presents a variety of major challenges. There are questions about expansion and ownership, the distribution of revenues from the interconnectors, and there is uncertainty in relation to the power price that the wind farms can achieve in different markets. These issues need to be coordinated and clarified before a European offshore grid can be realised. The expansion of offshore wind is dependent on the EU being able to coordinate a joint grid expansion and to regulate a common export market for offshore wind. With the high ambitions that the EU has regarding offshore wind, it is likely that the regulatory issues will be solved, and this is also what is assumed in the Low Emissions Scenario.

The expansion of offshore wind is dependent on a European power grid in the North Sea

Ending the subsidising of fossil fuels is an important policy instrument for facilitating, rather than hindering, the global energy transition

Hydropower production costs are low, and hydropower plants with reservoirs can also supply highly flexible electricity, which will be essential to compensate for the fluctuations in wind and solar power. Hydropower is more flexible than, for example, gas power, nuclear power and coal power, and can also be used to store energy for days, weeks and seasons. In addition, hydropower has some of the lowest greenhouse gas emissions per unit of energy produced compared to other renewable power production.

In the past 100 years, hydropower has undergone a process of industrialisation, and is therefore more developed than solar and wind power. The long history of hydropower also means that a significant proportion of hydropower plants will need upgrading and improvement the coming years. By 2030, 20 per cent of the world's hydropower plants will be over 55 years old, and the IEA estimates that 45 per cent of increased capacity will stem from repairs to existing power plants. Since 2016, annual growth in capacity has been around 1.8 per cent. Hydropower growth is expected up to 2050, but with a lower growth rate than solar and wind power, averaging around 1.5 per cent per year.* Hydropower production will surpass coal and gas power around 2040 and will continue to outstrip offshore wind in terms of capacity and production throughout the period.

In 2050, renewable energy will constitute almost 80 per cent of the total power generation, and around two-thirds will be generated from solar and wind power.

In some coal countries, such as China, India and Indonesia, the dynamic of lower renewable costs will not be enough. Coal is an integral part of society in these countries, and local coal prices are often regulated and significantly lower than global coal prices. The IMF estimates that the under-pricing of fossil energy sources will account for more than three per cent of global GDP in 2017.[54] Ending the subsidising of fossil fuels is an important policy instrument for facilitating, rather than hindering, the global energy transition.

Carbon capture and storage (CCS) is a possible alternative for the large coal countries, but this solution is expensive. In the Low Emissions Scenario, CCS will have a negligible role in the global power sector as costs will be high compared to other emission-free alternatives. Coal and gas power plant equipped with CCS technology will have high operating costs and therefore a low utilisation rate. CCS, on the other hand, will be important for cutting emissions in sectors that are more difficult to decarbonise through electrification, such as in industries with a high proportion of process emissions, in waste incineration and in the production of blue hydrogen from fossil gas (see Chapter 3). For example, around 60 per cent of CO_2 emissions in cement production are from coal encased in the raw material limestone. The coal is released when the limestone is heated, and CCS will be a good solution here. Within waste incineration, almost 75 per cent of the waste is currently from biogenic sources, and if all CO_2 is captured in a waste incineration plant, CCS will contribute to negative emissions, which is absolutely essential for achieving net zero emissions.

* Flexible hydropower is well suited to wide mountain areas where reservoirs can be established in existing lakes, and areas with nearby steep slopes for high head and with solid rock to build on without much need for concrete and rock protection. The number of locations that can offer this combination is limited.

Hydropower production will surpass coal and gas power around 2040. Hydropower plants with reservoirs are able to deliver very flexible electricity.

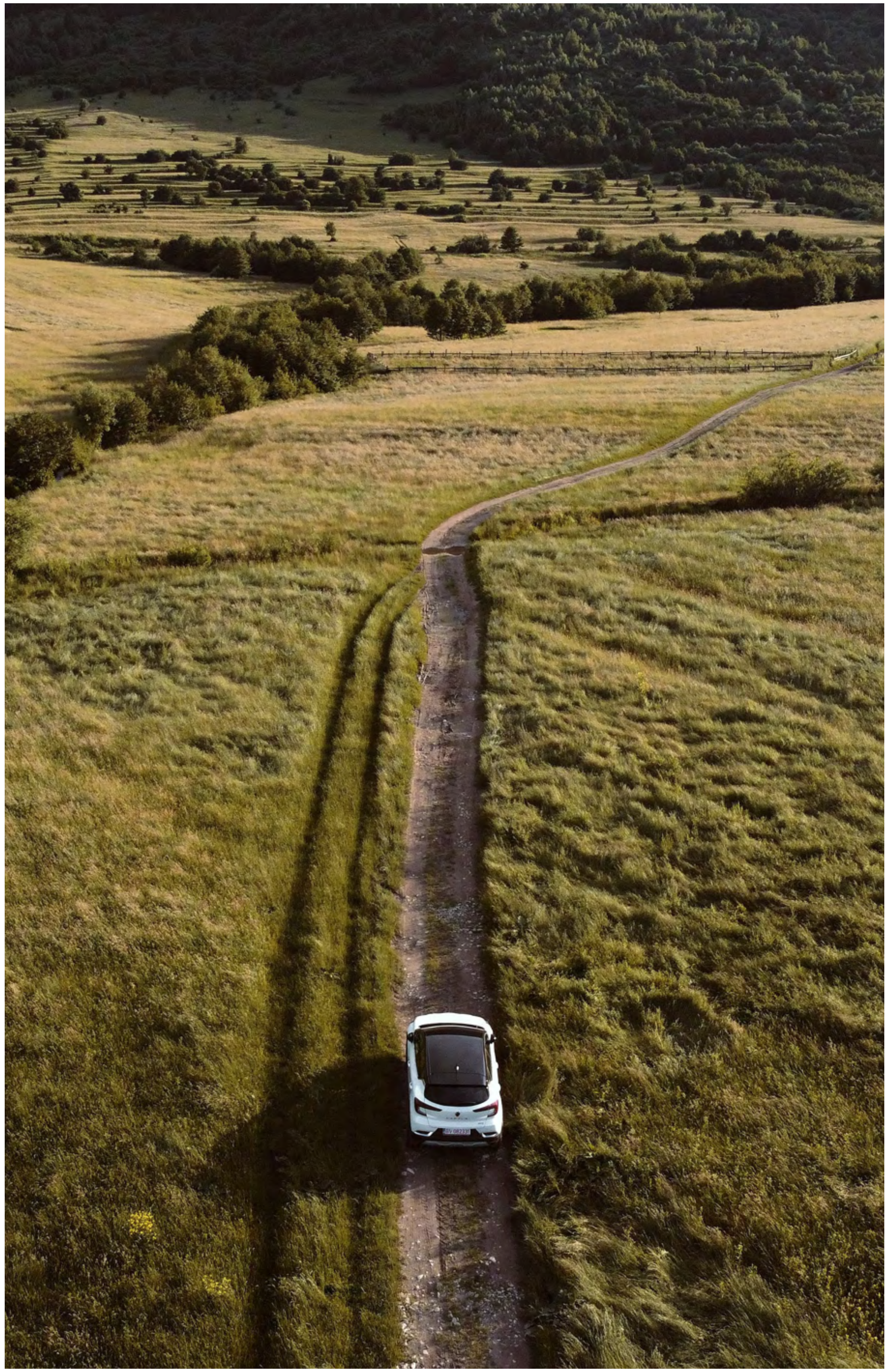
In the Low Emissions Scenario, nuclear power is estimated to grow by around 1 per cent annually between now and 2050, primarily driven by growth in Asia. Nuclear power is a thermal technology without CO_2 emissions, but new capacity is expensive compared to other emission-free alternatives. European nuclear power also has problems with long delays and cost overruns. The high costs, technical challenges and political climate all contribute to nuclear power playing a marginal but important role in the Low Emissions Scenario.
Much of the technological development in nuclear power is in small modular reactors (SMRs), where the reactors are smaller and can be mass-produced. The Low Emissions Scenario assumes that SMRs will achieve cost parity with traditional nuclear power around 2040.

Flexible solutions make it possible to handle the high share of cheap wind and solar power
Our analyses show that decarbonising the power systems, mainly with solar and wind power, is both possible and cost-effective.
The power markets can handle the high share of variable, renewable power production applied in the Low Emissions Scenario.* There are many different flexibility solutions, and renewable, flexible hydropower is a particularly good solution that covers various flexibility needs.
Where it is possible to expand the existing power capacity of hydropower, this can be a good solution. Countries without the prerequisites for flexible hydropower must resort to other, more expensive solutions.

Batteries can provide flexibility for short periods of time of one or a few hours. Prices are high today but are expected to fall quickly in line with the steadily increasing number of batteries being produced. The electrification of transport is one of the main drivers of this development, and smart charging of electric cars will be an important source of flexibility in the future.

Batteries are also able to fast react on imbalances in the system, so called fast frequency response. Many of the batteries built today are used for this purpose. To fast react on system imbalances are however not enough. To keep the power system stable physical inertia is needed for momentaneous imbalance response. Traditionally, thermal power plants and hydropower have contributed to this in the system, but in the future, this need will be met by hydropower and nuclear power, together with dedicated synchronous generators (see fact box 6).

* We run detailed power market models hour by hour with different weather-years over different time horizons for the countries and regions where Statkraft have a presence, in Europe, the Nordic countries, Asia and South America.



Recycling will be important for the demand for materials in batteries. However, the exponential growth in electric cars and energy storage means that only part of the demand growth will be met by recycling.

5

The energy transition's need for minerals and metals

The green energy transition will dramatically push up demand for some minerals and metals. In the IEA's "Net Zero to 2050" roadmap, total demand for minerals will increase sixfold by 2040. Increased investment in renewable power production, various types of energy storage, and electrification of the transport sector will lead to a large increase in the need for batteries, solar PV panels, wind turbines and electrical infrastructure[55].

The following minerals and metals are the most critical:

- **Distribution network:** copper, aluminium
- **Wind turbines:** steel, copper and rare earth metals
- **Solar PV panels:** steel, gas, aluminium, silicon, copper and silver
- **Batteries:** copper, nickel, lithium, cobalt, manganese, graphite and rare earth metals

A rapid energy transition will require substantial investment in the extraction and refining of these critical minerals.

Metals such as steel, aluminium and copper also have a number of uses outside the energy transition. The increased demand therefore constitutes a relatively smaller part of total demand, and the market has historically been able to adapt to large increases in demand over a relatively short period of time.
There are also large reserves of these minerals. The demand for steel has doubled since 2000, without prices rising significantly. Other minerals with few alternative uses and relatively little demand, e.g. cobalt, lithium, nickel and rare earth metals, are considered to be higher risk.

This is because the production/processing of these minerals tend to be concentrated in a handful of countries, which are often associated with varying degrees of political, social and environmental risk.

Inertia in the market and risk on the supply side can lead to short-term price fluctuations due to supply shortages of these minerals, but long-term structural price changes that will push up renewable technology costs are considered less likely. In the worst case, this could delay developments by a few years.
Should the risk or costs become too high, the materials can be substituted to a large extent, battery technology can be adapted, e.g. by using less cobalt, and the amount of other materials can be reduced.
Competing technologies to Li-ion batteries, which is the most common battery technology today, may also reduce risk.

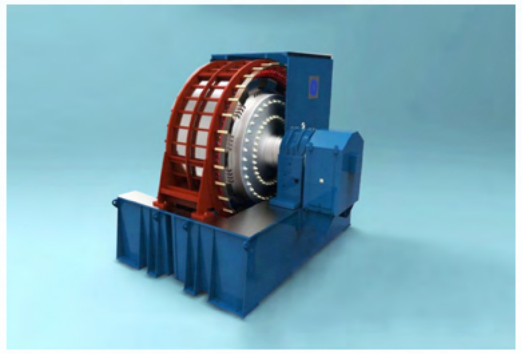
Recycling will be important for the demand for material in batteries, and according to industry standards in Europe, companies must achieve a recycling rate of 95 per cent for nickel, cobalt and copper by 2030, and 70 per cent for lithium. However, the exponential growth in electric cars and energy storage means that only part of the growth in demand will be met by recycling.

6

Rotating stabiliser can improve grid stability

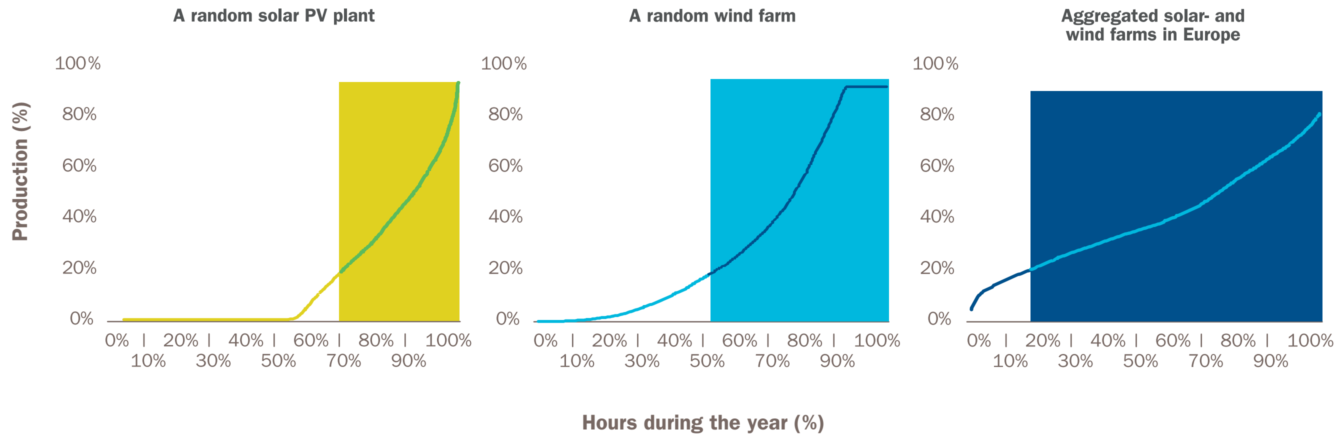
Increasing the share of renewable energy in the energy mix gives rise to a number of challenges in relation to stabilising the grid. Not only the need for a flexible power supply when the sun is not shining and the wind is not blowing, but also the fact that solar and wind power do not provide inertia to the system. Inertia plays an important role in maintaining the frequency at the right level, ensuring stability in the power grid. HVDC links (typically long subsea Power cables) that import and export power also do not provide inertia.

One technology that can help solve this problem is a so-called 'rotating stabiliser'. This is a large, heavy rotating synchronous machine (synchronous compensator/ condenser) that is connected to the grid. With the help of flywheels, the stabilisers can "store" kinetic energy (in the same way as hydro turbines) and thereby provide inertia to the system. The machine is designed



with a large mass to create as much inertia as possible. A rotating stabilizer can also generate and absorb reactive power and provide a large amount of short circuit current during transmission network faults, which helps with to stabilize the local voltage level during steady state and fault conditions. Statkraft is building two rotating stabilisers at Keith in Scotland, and this is scheduled for completion in the autumn of 2021.

15 All wind farms and solar PV plants have a very varied production pattern and several hours with no or very low production. If the production is combined (graph to the right), the profile becomes significantly more even. This is because the wind farms and solar PV plants in Europe often do not generate power at the same time.



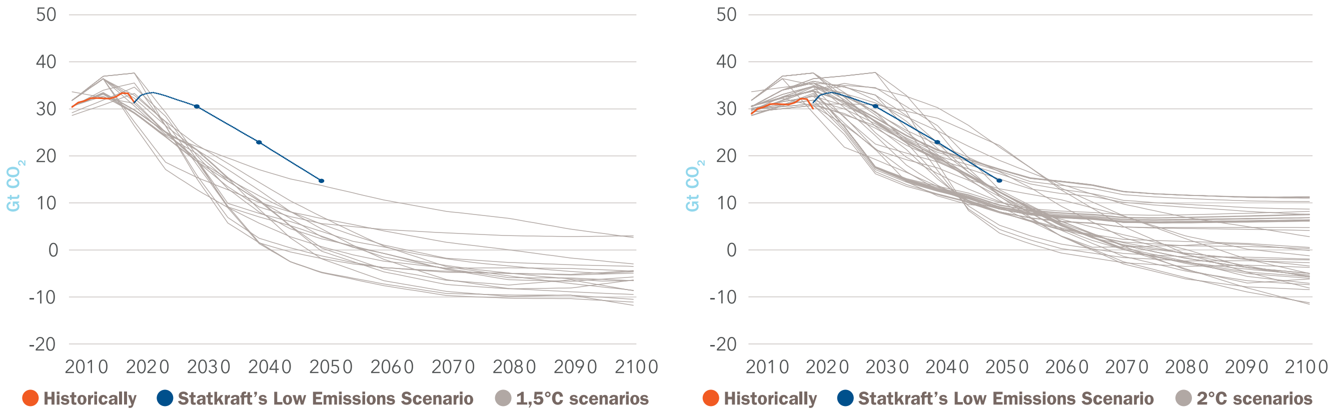
One option that reduces the need for flexibility is to expand solar and wind power in combination in the power system. We often see that it is cost-optimal to expand both solar and wind power in power systems with a high share of variable renewable power, even though one of these technologies has the best resources in the area. This is because the production profiles often complement each other. When the sun is not shining, the wind is often blowing, and when there is no wind, the sun is often shining. This complementation can take place within a 24-hour period or over longer periods and seasons. Solar and wind power complement each other best when the power system has a large geographical spread. Forming closer links between countries through cross-country interconnections is therefore a way of providing flexibility without building new flexible production or demand. Periods of high or low solar and wind production rarely occur simultaneously in all countries (Figure 15).

Technological development in solar and wind power can also help solve the challenges of flexibility. Solar PV panels with tracking and bifacial solar PV panels (which generate power from both sides of the panel) are increasingly being used to maximise power production from solar power plants and to improve the profile. Tracking is used to adjust the solar PV panels according to the position of the sun, which enables more direct sunlight to hit the panels. Installation and operating costs are higher for these, but they increase the utilisation rate of the solar power and help to even out the production profile in the plants.
This is becoming increasingly more common as costs fall, and is already standard in sunny countries.

It is often better to adapt consumption to production rather than to adapt production to consumption. Much of the growth in power demand in the Low Emissions Scenario is flexible. In buildings, electric heating in particular can be flexible for one or a few hours due to smart control systems. Smart systems can also help shift consumption, such as heating water and dishwashing, to favourable times of the day. In the transport sector, electric cars are a source of flexibility due to smart charging and the fact that they stand still 95 per cent of the time. Much of the future power production will come from the sun during the day, and this will typically result in lower power prices. Well-developed and smart charging infrastructure is necessary to exploit these hours, particularly in future workplaces. In the industry sector, our analyses show that green hydrogen production can be a major source of flexible power consumption (see Chapter 3). In traditional energy-intensive industry, some processes have the potential for flexible power consumption at a fairly low cost. Other industrial processes are completely dependent on an even supply of power.

There is a broad consensus that solar power and wind power will be the winners in the global energy system by 2050. This has been our conclusion in recent years, and different sensitivity analyses have arrived at the same result. However, we see that the composition of different flexibility solutions is quite sensitive to assumptions about costs and characteristics of the power systems. It is difficult to predict the optimal composition of the various flexibility solutions in the future. It is therefore crucial that these solutions can compete in the market on equal terms, without individual solutions being regulated separately.

16 Annual energy-related CO_2 emissions in Statkraft's Low Emissions Scenario compared with other two-degree scenarios (right) and 1.5-degree scenarios (left).[57*]



Despite relatively extensive volumes of flexibility resources, we still expect a significant change in both the daily and seasonal power price and generation profiles by 2050. This is primarily due to the large amount of solar in the power systems globally.

The Low Emissions Scenario is set to follow a 2°C emissions pathway

Energy-related greenhouse gas emissions account for around three quarters of the global greenhouse gas emissions[56].
In the Low Emissions Scenario, global energy-related CO_2 emissions will fall by almost 60 per cent between now and 2050, and we will end up with an annual emission of around 15 gigatons of CO_2 in 2050. The power sector and transport sector currently account for the largest share of energy-related CO_2 emissions, and emissions in these sectors will fall by 60% and 70% respectively over the period. This means that the energy-related CO_2 emissions in the Low Emissions Scenario are in line with the IPCC's 2°C pathway, but the reduction in emissions will still not be fast or deep enough to achieve a 1.5°C pathway (Figure 16).[11]

If the world is to limit emissions in line with a 1.5°C pathway, the transition must take place at an even faster pace and to an even greater extent than in the Low Emissions Scenario. The temperature has already risen about 1.1°C since pre-industrial times. This means that emissions must be reduced much faster if the temperature increase is to be limited to 1.5°C. This is also the conclusion of the IPCC, which states that the remaining carbon budget must almost be divided in three if the world is to limit global warming to 1.5°C as opposed to 2°C. Globally, the gap between the emissions in the Low Emissions Scenario and the emissions in the IPCC's average pathway for 1.5°C is around 10 Gt CO_2 in 2050. In addition, emissions fall significantly faster. As shown in Figure 16, all 1.5°C scenarios in the graph have lower global energy-related CO_2 emissions in 2050 than the Low Emissions Scenario.

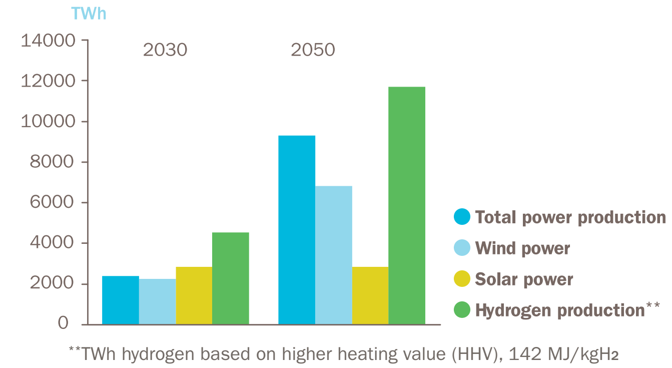
Virtually all of IPCC's scenarios that are consistent with 1.5°C include net negative CO_2 emissions after 2050, because the remaining carbon budget is too tight to enable sufficient cuts before 2050. Both natural solutions such as afforestation and technological solutions such as bioenergy with CCS help to remove CO_2 from the atmosphere.

Greenhouse gases other than CO_2 (e.g. CH_4, N_2O, SF_6, HFCs and CFCs) are often more difficult to limit than many CO_2 sources. The scenarios typically result in 30 per cent emission reductions of other greenhouse gases by 2030, 50 per cent by 2050 and 60 per cent by 2100. However, some scenarios already have more aggressive pathways for other greenhouse gases with zero emissions by 2050, which enables slightly higher CO_2 emissions from either fossil energy or land use, or less CO_2 removal.[58]

The COVID-19 pandemic has been a poignant reminder that major adverse events that seem unlikely may occur on a regular basis. There are many threshold limits or tipping points in the climate system that can lead to major, irreversible damage if they are exceeded, e.g. glacier melting, the collapse of the Greenland ice sheet or the weakening of the Gulf Stream. Avoiding such unknown tipping points is often cited as an important reason for limiting global warming to 1.5°C.

* To say that emission pathways correspond to global warming of 1.5°C or 2°C is a simplification. The 1.5°C scenarios shows energy-related CO_2 emissions from scenarios reported to the IPCC, 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 shows the scenarios that with a 50 or 66 per cent probability will limit global warming to below 2°C. The uncertainty is based both on assumptions about emissions that are not covered in the Low Emissions Scenario and on the uncertainty of the impact of greenhouse gases on the global temperature.

17 The difference between the Low Emissions Scenario and IEA net zero scenario. It requires a lot more electrification, renewables, and hydrogen to reach net zero by 2050.

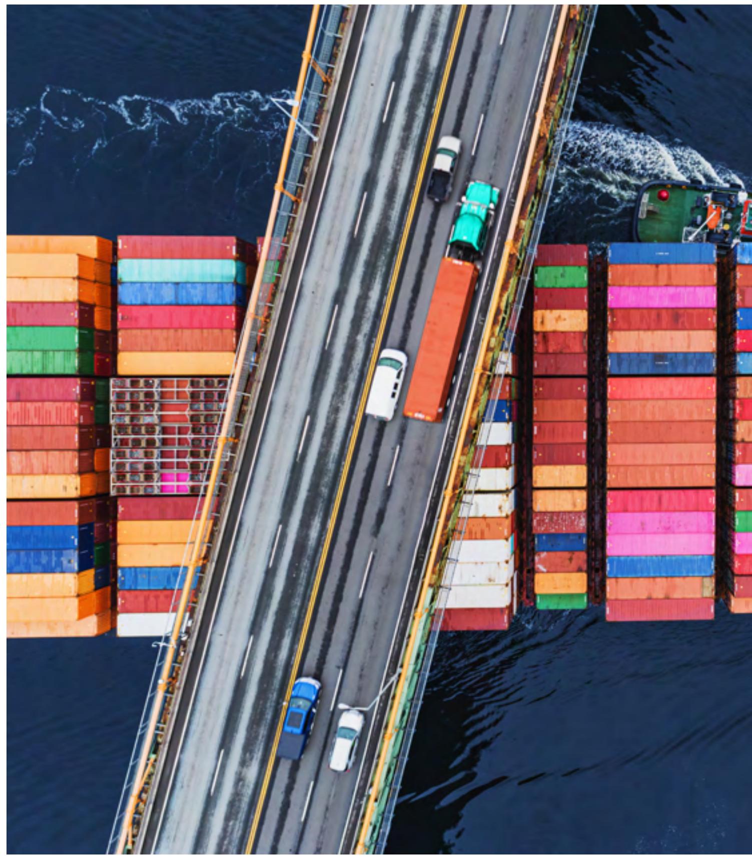


**TWh hydrogen based on higher heating value (HHV), 142 MJ/kgH_2

A short-term effect of the pandemic was that global greenhouse gas emissions fell by six per cent in 2020 as a result of the reduced mobility during lockdown and the economic downturn. If the temperature increase is to be limited to 1.5°C, global emissions must fall by about the same amount every year going forward. In 2021, a sharp increase is expected in global greenhouse gas emissions due to increased activity. If the world is to succeed in limiting global warming to 1.5°C, further reinforcement of policies will be urgently needed, followed by action. In order words, compared to the Low Emissions Scenario, a 1.5°C pathway will require more of everything, and measures will have to be implemented much faster.

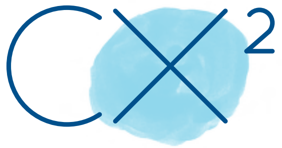
When analysing the global energy systems, it is natural to draw comparisons with the IEA's roadmap to net zero. Figure 17 shows that demand for primary energy is somewhat lower (-5 per cent) in the IEA's net zero emissions scenario in 2050 than in the Low Emissions Scenario, while power demand and solar and wind power production are somewhat higher (17, 15 and 44) per cent in 2050, respectively). As we approach zero emissions, it is emission-free hydrogen in particular that increases. The IEA's net zero emissions scenario estimates three times as much emission-free hydrogen in 2050 than the Low Emissions Scenario. Increased climate ambitions mean that focus moves passed renewable power and electric cars - where the market and technology are already driving much of the transition - to other sectors, such as industry and long-distance transport, where reducing emissions is more demanding and needs more political support. In these sectors, clean hydrogen will be crucial for meeting the climate targets.

Clean hydrogen is already an important climate solution in Statkraft's Low Emissions Scenario and must be further scaled for a 1.5°C emissions pathway. We take a closer look at clean hydrogen in the next chapter.



The power sector and transport sector currently account for the largest share of energy-related CO_2 emissions


3
CLEAN HYDROGEN:
FUELLING THE RACE
TO NET ZERO



Over the past year, Europe has taken a leading role globally in establishing a clean hydrogen industry

2%

The world currently produces 87 million tonnes of hydrogen. This accounts for about two percent of global greenhouse gas emissions

Hydrogen is needed to reach zero emissions

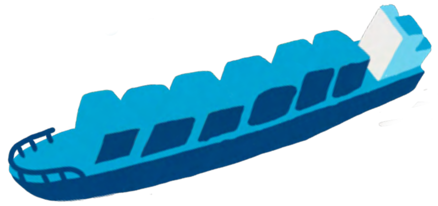
Hydrogen is the oldest and most abundant element in the universe. Hydrogen has been used in industry for a decade and clean hydrogen is considered to be one of the key solutions in countries' efforts to achieve net zero. This chapter examines the role of hydrogen in the energy transition up to 2050, with a focus on the interplay between hydrogen and the power market. Hydrogen links various sectors even more closely together. The power sector is becoming more central and the energy interaction more complex.

If the global emissions are to be minimised to almost zero, hydrogen will be an increasingly important contributor. There is currently a strong focus on cutting emissions in the power sector and using electricity directly to decarbonise the building-, transport- and industry sectors. The increasing climate ambitions are shifting the focus to areas where electrification as a means of reducing emissions is not viable. This means that clean hydrogen will become more prevalent in the energy system. Hydrogen is already the energy source of choice in some industrial processes. This consumption is emission-free if hydrogen is produced from renewable power (green hydrogen), and almost emission-free when using fossil gas with carbon capture and storage (blue hydrogen).

We are facing an industrial hydrogen race. A growing number of countries are now investing in clean hydrogen, and as of September this year, 20 countries as well as the EU have already launched their own hydrogen strategies. A further 23 countries are currently developing strategies, including the US, Brazil and China. The number of strategies has doubled since end of last year. Over the past two years, Europe has taken a leading role globally in establishing clean hydrogen industry, in terms of ambition, financial support and number of projects.[59]

6%

In addition to hydrogen use as feedstock in industry, emission-free hydrogen will cover around six percent of global energy world demand in 2050



The increase in total hydrogen demand up to 2050 will primarily come from new uses for hydrogen, such as long-distance transport

Hydrogen demand

Hydrogen has many different uses. It is already being used in industry, mainly as feedstock to produce ammonia for making fertilisers, and for methanol production and in oil refineries. Approximately 87 million tonnes of hydrogen are currently produced, and around 90 per cent is produced from fossil gas, oil and coal without carbon capture, which constitutes about 2 per cent of global greenhouse gases.[60]

Hydrogen demand is today split almost fifty-fifty between oil refineries and ammonia production. In the Low Emissions Scenario, current fossil hydrogen production for feedstock in industry will be almost fully replaced by both green and blue hydrogen by 2050. In addition to hydrogen consumption for feedstock in industry, clean hydrogen will cover around five per cent of the global energy demand by 2050. The increase in total hydrogen demand up to 2050 will primarily be from new uses of hydrogen, such as in the steel industry and long-distance transport (including clean ammonia for maritime transport). At the end of the period, we will also see some hydrogen demand in buildings and the power sector (Figure 18).

Our analyses for Europe show that clean hydrogen is often the most cost-effective climate alternative where using electricity directly is a challenge, for example in heavier transport over longer distances, high-temperature industrial heating processes and in feedstock in certain types of industrial processes, such as ammonia production. Customers are also increasingly demanding climate-friendly products throughout the value chain, such as green steel in the automotive industry. The next paragraphs include an overview of the hydrogen potential in the various sectors. We see that competition differs for the various hydrogen applications.

7

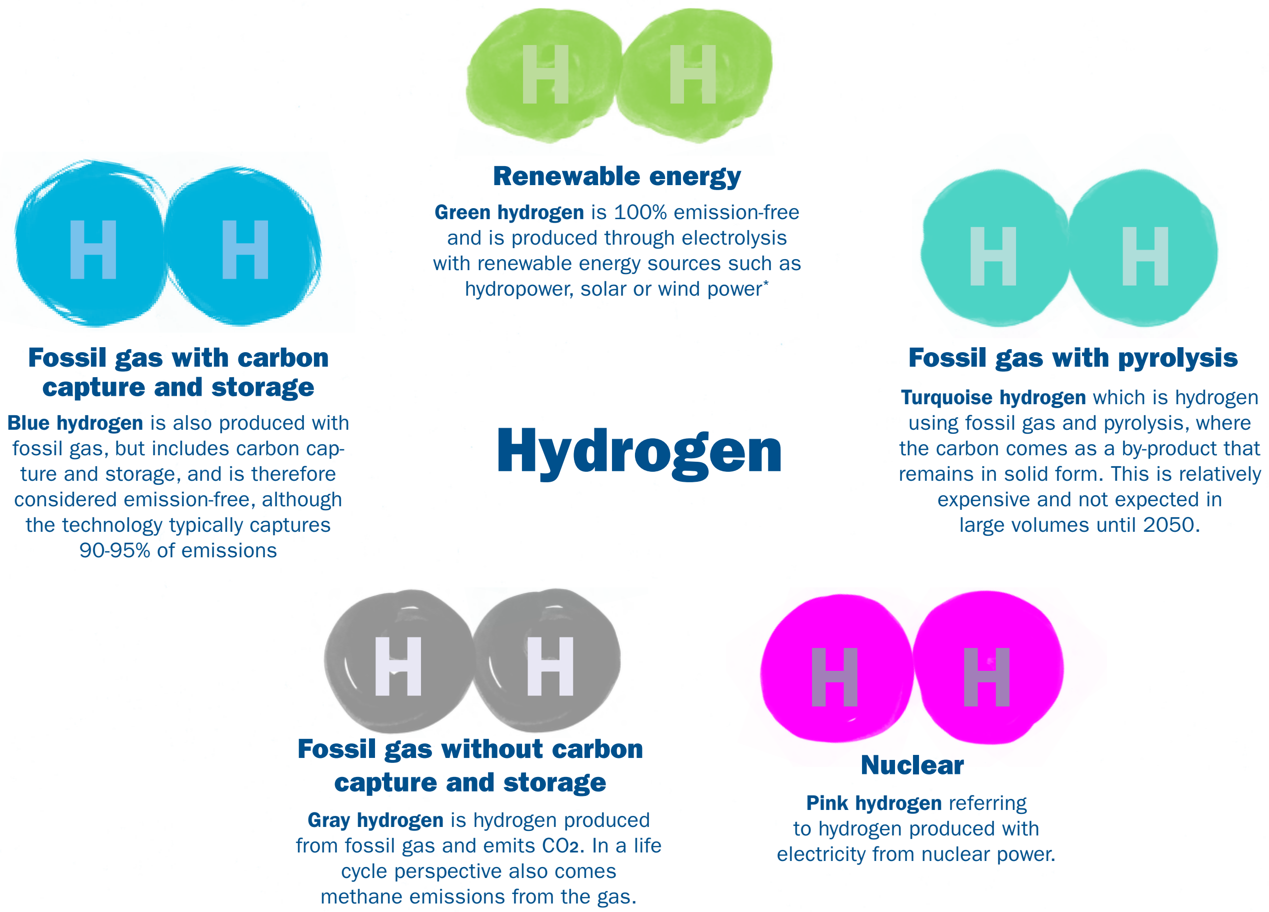
The many colours of clean hydrogen

Hydrogen can be produced from a variety of energy sources, both with and without greenhouse gas emissions. To simplify communication, a colour system is often used that indicates how the hydrogen is produced. The colours that are most common are grey, blue and green, and these are discussed in this chapter.

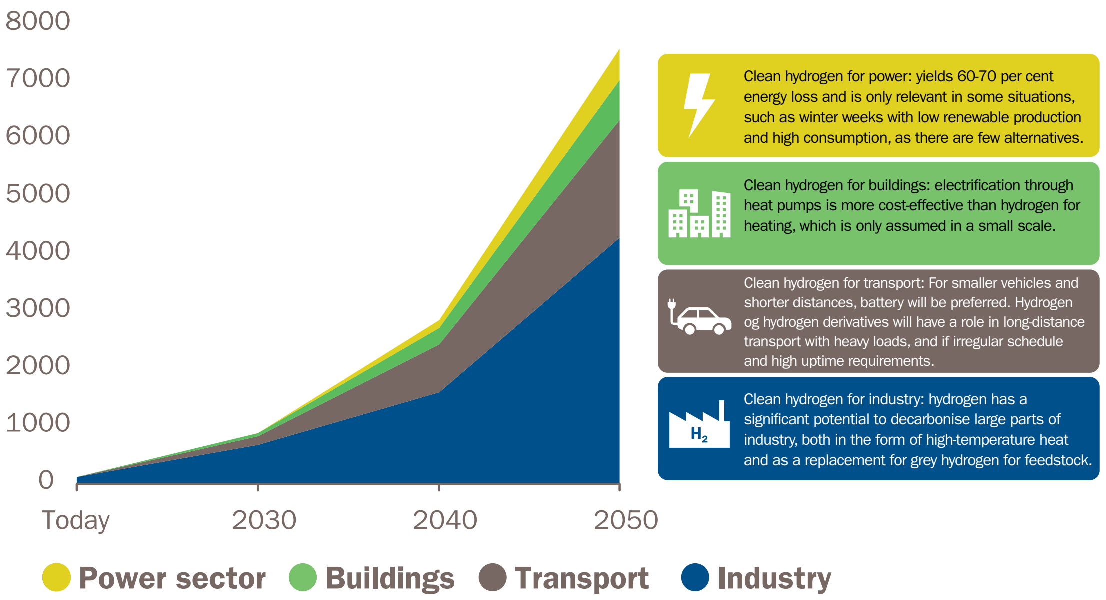
Grey hydrogen is produced from fossil gas and emits CO_2. *Blue* hydrogen is also produced from fossil gas but includes carbon capture and storage (CCS), and is therefore regarded as clean, even though the technology typically captures 90-95 per cent. *Green* hydrogen is 100 per cent emission-free and is produced using electrolysis and renewable energy sources such as hydropower, solar or wind power.*

Other colours are also referred to sometimes in articles or debates. Two other colours worth noting are *pink* hydrogen, which is hydrogen produced using electricity from nuclear power, and *turquoise* hydrogen, which is hydrogen that uses fossil gas and pyrolysis, where carbon is a by-product that remains in solid form. The latter is relatively expensive and large volumes are not expected until 2050. Both pink and turquoise hydrogen are also regarded as clean hydrogen

*Hydrogen from electrolyser is called "green" when the power is sourced either directly from a renewable power plant, is connected to the grid and combined with Guarantees of Origin (GoO) or is sourced from a fully decarbonised power system. Guarantees of Origin is an EU scheme that was established as part of the EU Renewables Directive to track the climate-friendly credentials of energy. The ability to track the climate and environmental footprint of products and services throughout the value chain is becoming increasingly important for investors, consumers, businesses, and governments. The EU member states have a statutory obligation to use the Guarantees of Origin instrument, while it is optional for consumers and end users to buy the certificates documenting energy use. The original scheme only covered electricity, but it was expanded in 2018 to include hydrogen and other renewable gases. The scheme was further proposed strengthened as part of the EU's 'Fit for 55' legislative package, which also proposes several sub-targets for renewable hydrogen and hydrogen-based synthetic fuels.



18 Global demand for clean hydrogen by sector (TWh)



Clean hydrogen in transport

In the transport sector, hydrogen and hydrogen derivatives will be beneficial in long-distance transport of heavy load.

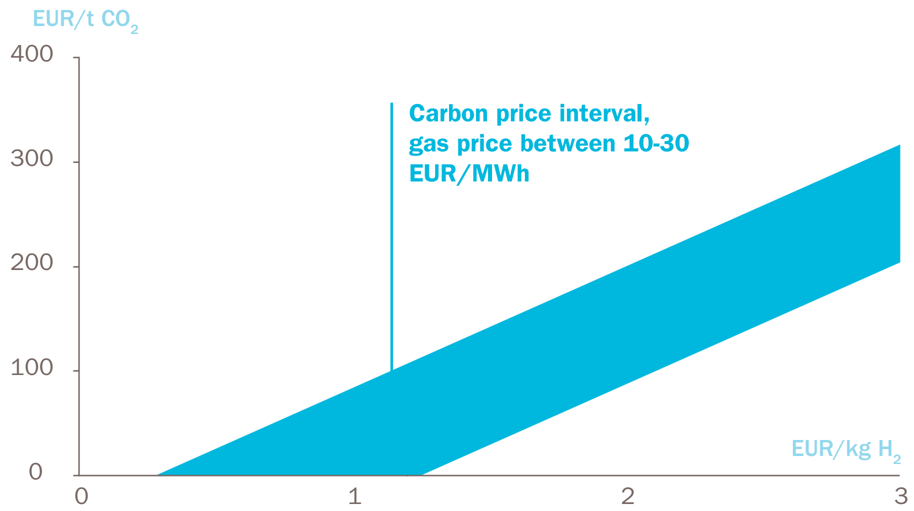
Road transport is currently responsible for around three fourth of CO_2 emissions from transport. Here we expect that clean hydrogen can play a role in long-distance heavy transport, as the volume and weight limitations of batteries and long recharge times will be a challenge for heavy duty trucks. Ordinary cars, vans and smaller trucks are expected to be battery powered, with some exceptions where driving distance and recharge time are critical. The roll-out of hydrogen and battery-electric vehicles will require substantial investment in infrastructure (see Chapter 2). Both the purchase cost and the total cost of ownership are lowest for diesel trucks today, while the costs for both battery-electric and hydrogen-powered trucks are expected to fall considerably over the next 10-20 years. Stricter emission requirements for heavy transport are expected in the future, in particular in Europe, the United States and China.

In the Low Emissions Scenario, both battery- and hydrogen-powered trucks will be cost competitive with diesel (total cost of ownership incl. carbon tax) by 2030. The choice between battery-electric or hydrogen-powered trucks mainly depends on driving time, load and flexibility needs. The purchase cost for the different vehicles is expected to converge around 2040. For driving in the city and local goods transport with a relatively regular driving pattern, we expect battery-electric trucks to be the preferred option, while hydrogen-powered trucks will have a role in long-distance heavy transport and transport with irregular driving patterns or high uptime requirements.

Clean hydrogen will also be crucial for the decarbonisation of ***maritime transport***. For ferries and riverboats travelling short distances, battery-electric or compressed hydrogen with fuel cells will be suitable. Compressed hydrogen will also be suitable for speedboats and medium-range coastal vessels. The low volumetric energy density of compressed hydrogen makes it difficult to store large quantities for longer distances. Liquid hydrogen will have high conversion costs and require extremely low temperatures. Ammonia ships are therefore emerging as a relevant clean alternative for long distances at sea, as clean ammonia has a higher energy density than compressed or liquid hydrogen. Green ammonia is produced from green hydrogen and nitrogen, and can be used as fuel in a fuel cell or in an internal combustion engine. Around 150 million tonnes of fossil ammonia are currently produced every year, and this is transported by sea. Infrastructure is therefore already in place. Ammonia is a toxic gas that requires strict safety practices. It is not therefore expected to be used on ships with passengers. The marine heavy fuel oil used today is cheap and has a high energy density, and our analyses show that clean alternatives will not be competitive without a high carbon price and political support. The transition in the shipping industry will take time, and we have assumed that green ammonia will mainly be used as from 2030. For the world to reach net-zero, emission-free hydrogen will also play a role in the other transport segments, such as ***aviation***, primarily in the form of synthetic fuel.

19 The carbon price needed to trigger switch from grey to green ammonia*

* 1 EUR/kg hydrogen equals 25,4 EUR/MWh (HHV)



Clean hydrogen in industry

The industry sector accounts for 24 per cent of the global CO_2 emissions. Approximately 60 per cent of this is from energy use, and process emissions make up the other 40 per cent. Our analyses show that clean hydrogen has a large potential in the decarbonisation of large parts of the industry sector, both in the form of energy for heat and feedstock. Hydrogen is a suitable solution for achieving ***high-temperature heat*** in industry, while electricity in the form of heat pumps and boilers is most useful for low- and medium-temperature heat below 500°C.

In the Low Emissions Scenario, clean hydrogen covers seven per cent of the global final energy demand in industry in 2050. This share will increase in a 1.5°C pathway.

The ***steel industry*** today accounts for around seven per cent of the global CO_2 emissions. The largest contributor to these emissions stem from the process of producing iron from iron ore. The most common methodology is to use a blast furnace fuelled with coking coal. In this process, coking coal is used both as a reducing agent and as a high-heat energy source. By adding hydrogen, the process becomes more efficient, less coal is needed, and it is possible to reduce CO_2 emissions with around 20 per cent. The second methodology to produce iron from iron ore is a process called Direct Reduction of Iron (DRI). Fossil gas has historically been used in this process and is common in countries with high share of domestic gas resources. Fossil gas can be replaced by green hydrogen and in this way the DRI process can become 100% emission-free.[61]

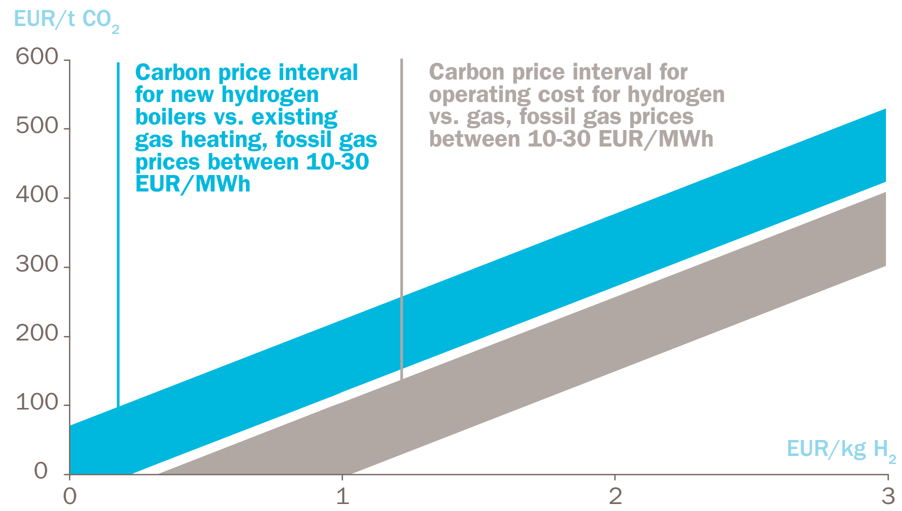
The last part of the steel making process, to make steel from iron, can use an electric arc furnace. This process is emission-free when electricity comes from renewable sources and is commercially available and commonly used today. In an electric arc furnace, iron can also be mixed with recycled steel.[62]

The ***ammonia industry*** currently covers about 50 per cent of the global hydrogen demand, which corresponds to one per cent of global CO_2 emissions. Replacing fossil hydrogen with clean hydrogen will be relatively easy in this industry. Ammonia production involves adding nitrogen to hydrogen in a Haber-Bosch process and converting these elements to ammonia (NH_3). Clean ammonia will also be used in new applications with the growing pressure to decarbonise across sectors, such as a fuel in the maritime sector and as an energy carrier.

We have compared the costs of ammonia produced with green and grey hydrogen. Our analyses show that green ammonia will need a carbon price of EUR 100-200 per tonne CO_2 in order to be competitive with grey ammonia. This assumes a price of EUR 2/kg for hydrogen and a gas price of EUR 10-30/MWh.

The ammonia Haber-Bosch process requires an even supply of hydrogen. It is therefore assumed that an electrolyser is connected to the power grid. In order to enable power price optimisation, the electrolyser is also connected to a small storage tank to cover flat weekly consumption. The analysis is based on an alkaline electrolyser located at the same place as the ammonia Haber-Bosch process. Costs associated with water for hydrogen production and the distribution and storage of ammonia have not been taken into account.**

20 Carbon price needed to trigger a switch from existing gas heating to a new hydrogen boiler for heating in building



Clean hydrogen in buildings

Today, heating in buildings accounts for around six per cent of global greenhouse gas emissions due to the use of fossil fuels. In the Low Emissions Scenario, the decarbonisation of buildings will mainly entail direct electrification in the form of electric boilers, electric heaters and heat pumps. These are more cost-effective heating solutions than clean hydrogen.

We have compared the costs of heating buildings with hydrogen boilers and fossil gas boilers.Our analyses show that for ***hydrogen boilers*** to outcompete existing gas boilers in a household, a high carbon price will be required in combination with a decline in hydrogen costs. The investment cost will also need to be reduced to the same level as for gas boilers today. A carbon price around EUR 300 per tonnes CO_2 is needed for green hydrogen to compete with fossil gas boiler, assuming hydrogen price of EUR 2/kg and a gas price of EUR 10-30/MWh (Figure 20).*** Infrastructure costs are excluded from the calculation. Clean hydrogen will be relatively more competitive than fossil gas if the switch to hydrogen takes place during planned upgrades or replacements of existing gas systems.

The Low Emissions Scenario estimates that clean hydrogen will cover up to 2 per cent of global final energy demand in buildings in 2050.

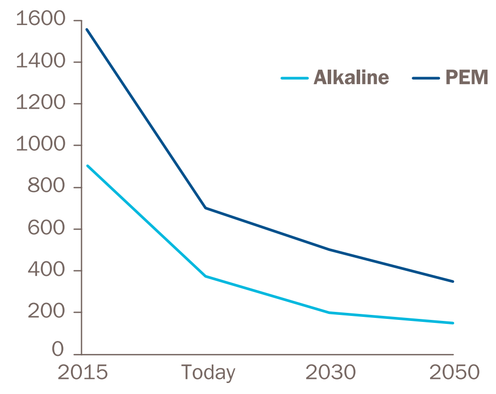
Hydrogen faces competition in all sectors

The various applications of hydrogen will face competition from alternative fossil and low carbon solutions in all sectors. Where direct use of electricity is possible, such as for electric cars and heat pumps, the higher efficiency will make this form of energy in general more cost-effective than hydrogen. Meanwhile, for applications where the direct use of electricity is challenging, clean hydrogen will often be attractive. For example in replacing fossil hydrogen use in industry with clean hydrogen and using clean hydrogen and ammonia in long distance transport. Costs are expected to fall significantly and clean hydrogen is to become gradually more competitive. For green hydrogen, the interaction with the power market will be an important cost driver, which we will now dive deeper into.

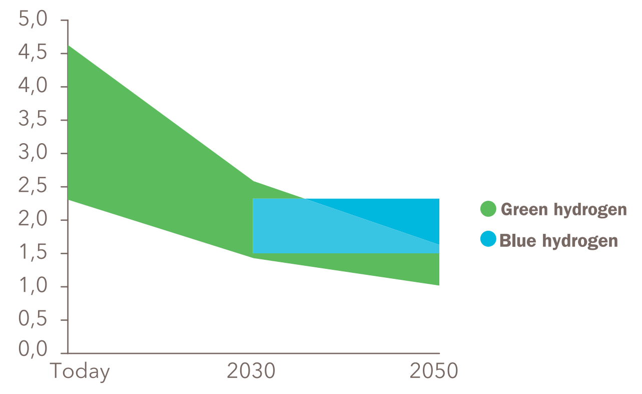
** Green hydrogen is produced by splitting water molecules into oxygen and hydrogen using an electrolyser. Approximately 10 kg of distilled water is needed for every kilo of green hydrogen, which corresponds to 15-20 kg of fresh water. Water purification accounts for around 5-6 per cent of the cost of producing hydrogen according to IHS. It is assumed that enough water will be available, either fresh water or desalinated water. Water consumption is not expected to be a limiting factor in the development of green hydrogen.

*** Other assumptions: a heating demand of 10 000 kWh/year, boiler efficiency is assumed 92% for gas boiler and 90% for hydrogen boiler. Carbon content in gas fuel is 201 $kgCO_2$/MWh and 1 EUR/kg hydrogen equals 25,4 EUR/MWh (HHV).

21 Electrolyser costs, 100 MW (EUR/kW)



22 Production costs for green hydrogen without grid connection, compared to blue (EUR/kg) (excl. transport and storage)



Electrolyser costs have declined by around 60% the last five years

Hydrogen production and the interplay with the power market

In the Low Emissions Scenario, the demand for power will increase by around ten per cent by 2050 as a result of green hydrogen in energy use, but there are large regional differences. With high climate ambitions, power demand for green hydrogen in Europe will increase by 20-25 per cent by 2050. This corresponds to more than 1,000 TWh of new, emission-free power production. This sounds like a lot - and it is - but the increase is viable because the power demand is flexible, particularly when an electrolyser is connected to storage solutions.

Green hydrogen and power interact on several levels, which makes the markets and analyses complex. In our power market models, the importance of hydrogen for the power systems in Europe increases steadily up to 2050, and as electrolyser costs fall, power prices will gradually have more impact on hydrogen costs.

The cost of electrolysers and the power price will dictate the price of green hydrogen, while the cost of water is relatively modest. In the last five years, the costs for electrolysers have fallen by around 60 per cent and are expected to fall further due to greater standardisation, automation and technology improvements.

Investment costs for green hydrogen production could fall a further 60 per cent by 2050. Statkraft's analyses show that clean hydrogen will increasingly be produced both from renewable energy via green, but also from blue, and these will complement each other, e.g. by using the same infrastructure (see Figures 21 and 22).

While the cost of green hydrogen is determined by the cost of electrolysers and the power price, blue hydrogen costs are dictated by the cost of fossil gas and CCS. The capital cost for blue hydrogen will be considerably higher than for grey hydrogen production without carbon capture. At the same time, operating costs will increase. In addition, the cost of transporting and storing carbon may be considerable.

The costs of getting hydrogen to the end user will also largely depend on the need for storage and transportation, as well as the demand profile and needs of the customer.

Hydrogen production connected to the power grid is normally better than off-grid solutions.

It is important for the power system that the increased power demand from green hydrogen production offers hourly, daily, weekly and monthly flexibility. This lays a good foundation for meeting the power demand for hydrogen production with renewable energy. Our analyses show that, in most cases, green hydrogen production connected to the power grid is a better solution than hydrogen production that is completely disconnected from the grid. This is because grid-connected electrolysers can utilise the resources in the sector-coupled energy system more efficiently.

Green hydrogen connected to the grid can generate hydrogen when power supply in the system is high and power prices are low, which is often the case when there is a lot of sun and wind. This reduces hydrogen production costs whilst helping to balance the power systems, which is necessary due to the large share of variable power production from solar and wind sources. Hydrogen demand does not tend to correspond directly with an abundance of sun and wind and times when power prices are low. The hydrogen therefore needs to be stored in order to keep production costs down. Seasonal storage can be beneficial in markets with significant power price differences between seasons, for example in Europe. Salt caverns are well suited for large hydrogen storage, and they appear to have the lowest cost per volume of stored hydrogen.

As hydrogen can be produced flexibly, green hydrogen production alone will boost low power prices in the power system. All else equal, renewable power production will then become more profitable due to the somewhat higher power prices during times with high levels of solar and wind power.* How these market dynamics develop in detail in the future depends on several factors, such as infrastructure build-out for power and hydrogen, the share of solar and wind in the power system, and the structure of taxes and tariffs for power and hydrogen.

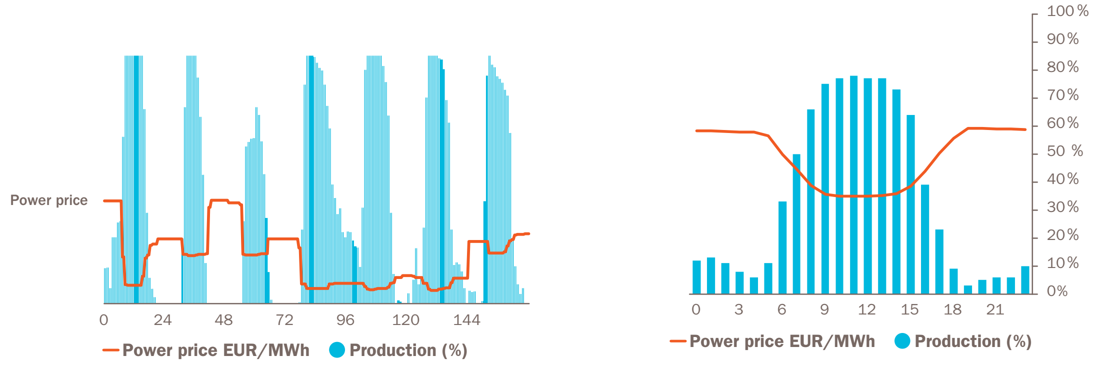
As electrolysers become more flexible, they will also be able to provide system services. Electrolysers will therefore not only provide hourly, daily and weekly flexibility, they will also be flexible enough to stop or start production in a matter of minutes in order to help the power system deal with short-term imbalances in frequency due to incorrect forecasts for sun and wind, power plant outages, etc.

Green hydrogen production from variable renewable energy that is completely separate from the grid may be pertinent, especially in isolated areas and in places where the power grid is not well developed. This will usually require large storage solutions which drives up costs, as hydrogen production becomes variable, while the need for hydrogen is usually even. Large hydrogen storage will be particularly expensive if hydrogen production is linked to solar power plants in parts of the world with a clear summer-winter solar radiation profile.

Cooperation between nations helps making hydrogen production more affordable

* Flexible hydrogen production also reduces the number of hours where the power plant need to shut down variable power production to balance the grid (curtailment).

23 Hydrogen production hour by hour as a function of power price, over a week and a day.



Hydrogen production is flexible. Statkraft's analyses show that in the future, electrolysers will tend to run during the day. The graph to the left shows green hydrogen production during a week compared to the power price and the graph to the right shows the average hourly production of green hydrogen compared to the average power price throughout the day

As electrolysers become more flexible, they will also be able to provide system services.* Electrolysers will therefore not only provide hourly, daily and weekly flexibility, they will also be flexible enough to stop or start production in a matter of minutes in order to help the power system deal with short-term imbalances in frequency due to incorrect forecasts for sun and wind, power plant outages, etc.

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The power price variations will make it profitable to build infrastructure for storage and transport

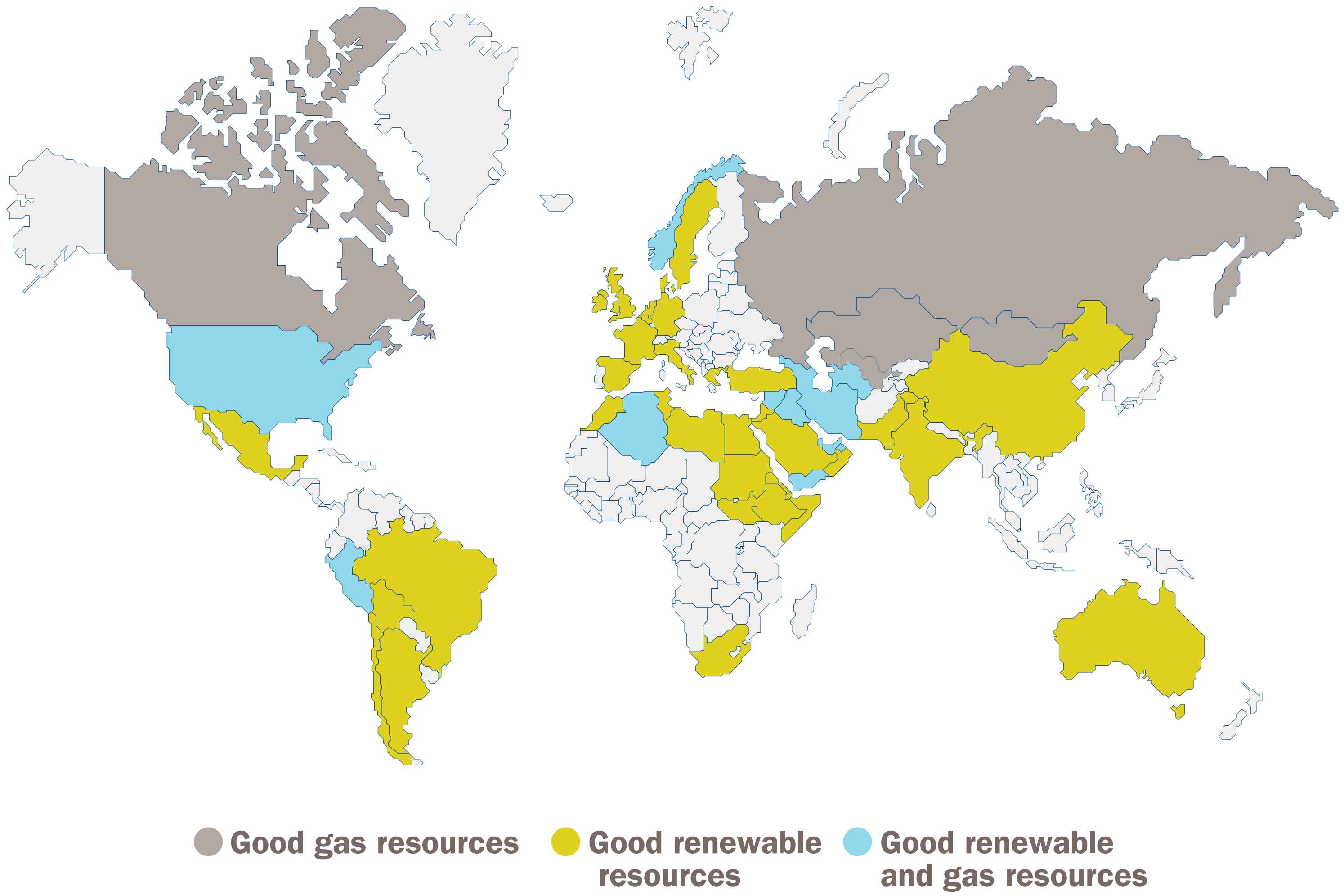
Today's grey hydrogen is mainly produced close to demand, but around 2,600 km of hydrogen pipelines in Europe and the United States already transport 100 per cent hydrogen for use in industry. Clean hydrogen is expected to be produced and distributed locally before 2030, either in industrial clusters or at filling stations for heavy transport. The hydrogen infrastructure for larger volumes and longer distances is then expected to gradually be built-out as the demand for hydrogen grows and the share of renewables in the power mix increases.

Our analyses show that the costs of producing green hydrogen vary considerably across countries and from month to month. The monthly price variations and the variations between countries in Europe up to 2050 will make it profitable to build infrastructure for seasonal storage and regional transport. This will enable hydrogen production to be run as flexibly as possible and to better exploit the renewable resources in the power system.

In areas where the infrastructure is not well developed, the solution will typically be a small storage tank in proximity to either the consumer or the producer. This makes it possible to run the electrolyser flexibly within a few days, but not much more. This solution typically leads to high hydrogen costs in the winter in many countries since solar power production is low and power demand is high. If the infrastructure is expanded and include seasonal hydrogen storage, green hydrogen production can also exploit the power price difference within the year and produce most of the hydrogen needed in the summer. In the future, we expect that hydrogen production will largely follow the solar power profile. Seasonal storage impacts on hydrogen costs and power markets. For example, greater use of seasonal storage in Germany will reduce monthly power prices in the winter and push them up in the summer. As an example, our power market models show a change in monthly power prices of 10-25 per cent in 2050 when we increase seasonal storage from half of the hydrogen demand to cover three quarters.

Hydrogen infrastructure makes it possible to link areas with highly variable renewable energy production to larger demand centres within a country or between regions, for example from north Germany to south Germany, or from southern Europe to north western Europe (see Figure 24 and fact box 8 for an overview of transport and storage solutions).

Map **Good gas and renewable resources for hydrogen production**



* PEM (polymer electrolyte membrane) electrolysers are particularly well suited for this.

Case: Analysis of different storage and transport solutions gives different costs for green hydrogen supplied in Germany in 2050

German industry currently uses around 55 TWh of hydrogen, primarily from fossil energy. In June 2020, Germany launched a national hydrogen strategy aimed at developing a national green hydrogen industry. This includes an ambition of building 5 GW of electrolyser capacity by 2030, as well as considerable imports of clean hydrogen. We have compared the costs of supplying green hydrogen to Germany in 2050 using four different routes, and assuming flat demand throughout the year:

- Case 1: Produce green hydrogen locally in Germany without seasonal storage
- Case 2: Produce green hydrogen locally in Germany with seasonal storage
- Case 3: Produce green hydrogen in southern Italy and pipe to Germany
- Case 4: Produce green hydrogen in Chile and ship as green ammonia to Germany and convert back to hydrogen

Due to the low volumetric energy density of hydrogen, higher costs will occur when hydrogen has to be transported or stored since hydrogen must either be compressed, liquefied or converted to hydrogen derivatives (such as ammonia and methanol). Processing that increases the volumetric energy density will therefore have to be balanced against reduced efficiency and increased costs. The four cases and results are presented in more detail below.

Case 1
Hydrogen is produced locally in Germany without seasonal storage, but with weekly storage in a compressed tank. This will cover an even demand over the week and year. As the power price will be higher in the winter and the electrolyser cannot be run flexibly over a long period of time, the production costs in this case will be relatively high (Figure 24(1)).

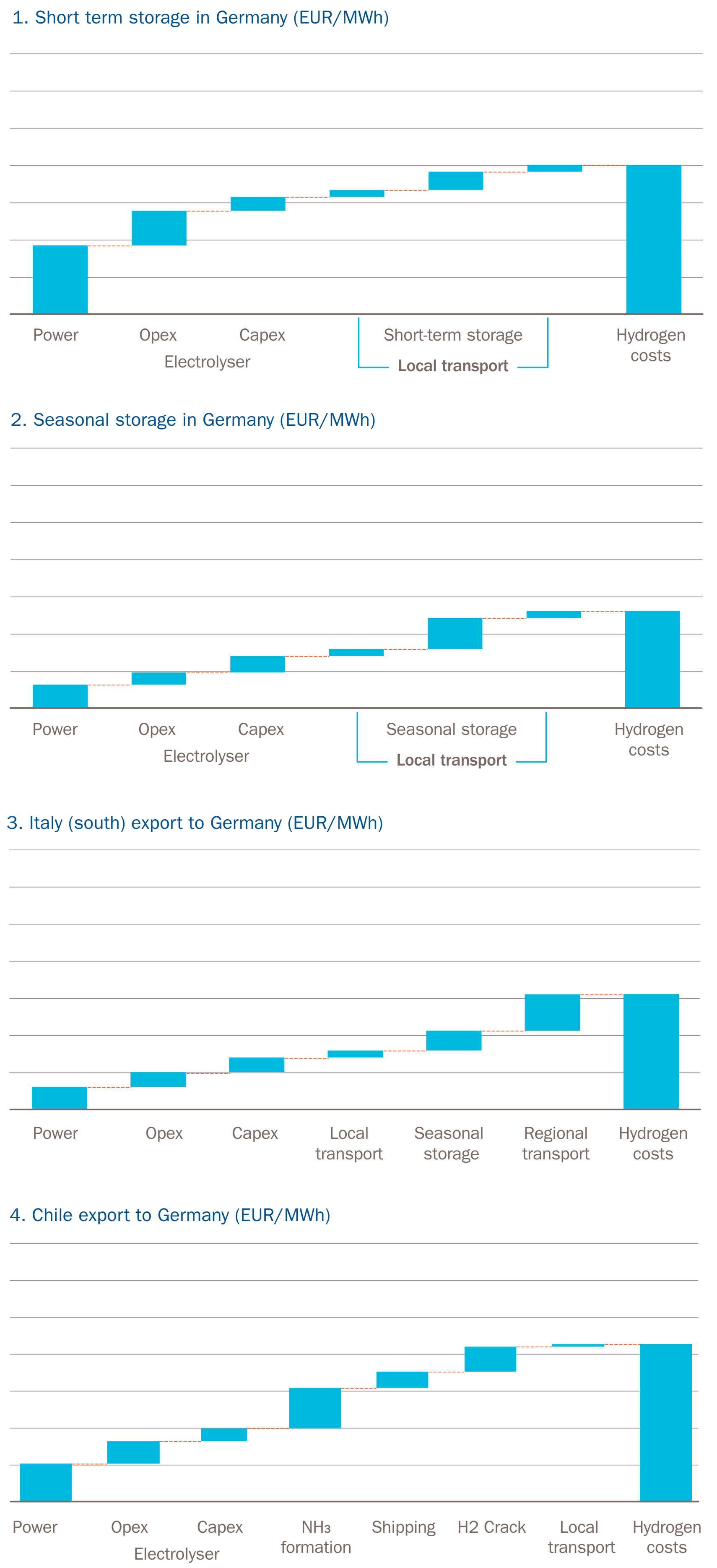
Case 2
Hydrogen is produced locally in Germany with seasonal storage. In this case, 70 per cent more hydrogen is produced in the summer, and this is stored in salt caverns and used to meet the winter demand for hydrogen. A compressed tank is also used for hourly storage within the day. Seasonal storage is used for both weekly storage and monthly storage. In this case, it is possible to produce hydrogen in the hours with the lowest power price, and the production costs including storage will be much lower than in case 1 (Figure 24(2)). There is substantial potential in Germany and north western Europe to build new salt caverns or expand existing caverns for large-scale storage over several months

Case 3
Hydrogen is produced in southern Italy and piped to Germany. Here, the electrolyser is combined with a small hydrogen tank for short-term hourly storage. The countries in North Africa also have relatively low hydrogen production costs throughout the year because of the good sun conditions, and where it is possible to have a physical hydrogen pipeline connection to Germany. In this case, production costs are competitive with seasonal storage in Germany (Figure 24(3)).

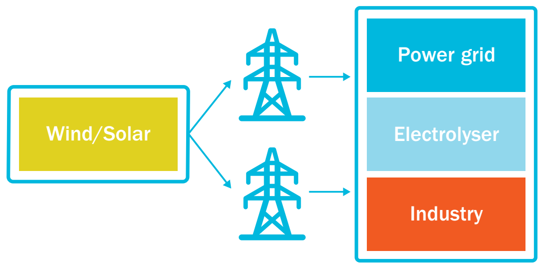
Case 4
Hydrogen is produced in Chile using renewable energy. The hydrogen is then converted to green ammonia and shipped to Germany, where it is converted back to hydrogen and used to cover the German demand. Ammonia has a higher energy density than compressed and liquid hydrogen and this can therefore be a suitable way of storing and transporting hydrogen over long distances. The cost analysis includes local transportation and storage in both Chile and Germany, as well as conversion to and from hydrogen and shipping from Chile to Germany. The costs of converting to ammonia and back to hydrogen makes this a relatively expensive solution (Figure 24(4)).

Comparisons of the four cases for 2050 show that German power price variations make seasonal storage of hydrogen attractive (case 2, Figure 24(2)). Seasonal storage will be able to compete with hydrogen piped from southern Europe and North Africa (case 3, Figure 24(3)). If a large volume of hydrogen is to be transported, piping it is the most attractive option. Both new and converted gas pipelines are a significantly cheaper option than converting hydrogen to ammonia and sending it by sea. 23 gas transmission system operators are now investigating the possibilities for a large hydrogen network that connects industrial clusters in Europe with areas with an abundance of renewable energy. The vision is 39,700 km of dedicated hydrogen pipelines by 2040.[65] For longer distances where physical pipelines present practical problems, shipping hydrogen as a hydrogen derivative, such as green ammonia, may be an option. This is especially relevant if ammonia is the end product (fertiliser industry, marine heavy fuel oil). There is already a global ammonia market today, which means that parts of the infrastructure is already in place. However, the cost of converting hydrogen to ammonia in Chile, and conversion from green ammonia back to hydrogen in Germany makes this solution relatively more expensive than seasonal storage and/or regional transport via pipelines. An interesting finding in this case is that even with long transport distance, transportation costs have a small part of the total costs compared to the cost of producing and converting hydrogen (Figure 24(4)).

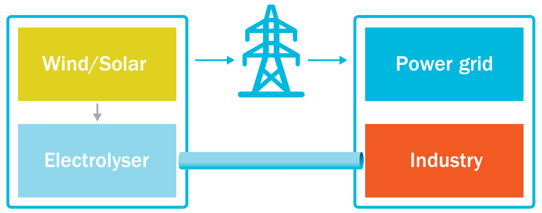
24 Four different cases for supplying green hydrogen to Germany in 2050 (EUR/TWh H_2)



Without hydrogen infrastructure



With hydrogen infrastructure



Hydrogen contributes to emission-free, flexible power production when alternatives are limited

Vast amounts of energy are lost when generating power from hydrogen. About 20-30 per cent of the energy is lost in the electrolyser, and another 40 per cent is lost in power production (unless the waste heat is utilised in other sectors, such as district heating). This equates to an overall energy loss of 60-70 per cent. Using hydrogen for power production is therefore not a good solution in most cases. In some situations, such as winter weeks with low renewable power production and high consumption, the lack of other alternatives means that power production from hydrogen can still be an attractive emission-free solution for peak power supply. The investment cost for hydrogen turbines is relatively modest compared to alternative solutions, which is crucial for production capacity with limited running hours. Flexible hydropower is another good option in geographies where this is possible. Expanding the power capacity of existing hydropower is one of the most economically attractive options for covering long-term flexibility needs in the power market.

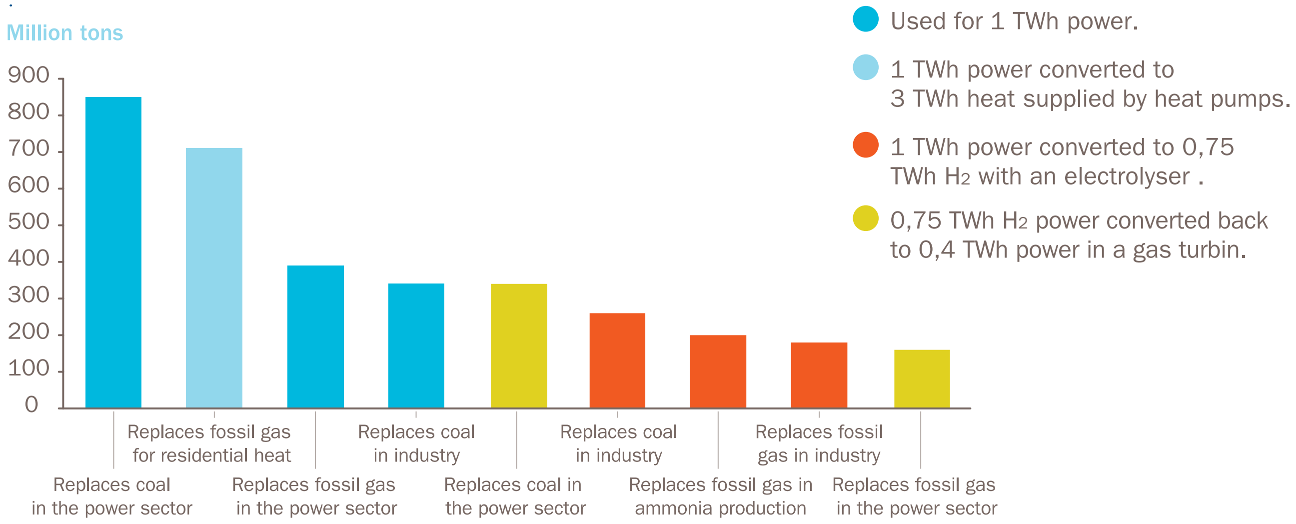
Green hydrogen production and hydrogen infrastructure can complement power grid expansion

When the share of variable power production is high, power prices can be both very low and very high. Flexible green hydrogen production utilises the low prices in the power market. This gives hydrogen production an advantage in markets with a high share of intermittent power production and higher price variation. However, the advantage of hydrogen production in markets that have less price variation, e.g. due to high share of other forms of flexibility, particularly seasonal flexibility, is that smaller hydrogen storage solutions are needed. Where large volumes of green, flexible hydrogen are produced, this will even out the difference in power prices, which in turn will impact on revenues and the benefit of other flexibility solutions, such as large pumped storage power plants.*

Local hydrogen production combined with hydrogen infrastructure can help move energy in the form of hydrogen from areas with good renewable resources, either onshore or offshore, to areas that need hydrogen. A well-developed hydrogen infrastructure can complement power grids. In areas with local bottlenecks where the grid does not have the capacity to transfer enough power between areas, this can be beneficial. Although hydrogen infrastructure can support the power grid in certain areas and help address local bottleneck problems, it is still key to have a well-developed power grid and cross-country interconnections that connect power systems across regions and countries in order to ensure cost-optimal integration of increased shares of renewable power production.[67]

* The various flexibility solutions will help to raise low power prices and curb high prices. When different types of flexibility solutions compete with each other, this helps to curb price variations. The more actors entering the market, the smaller the marginal income per flexibility solution, all else equal.

25 CO_2 reduction when replacing fossil fuels with clean power. All emissions need to be cut to achieve zero emissions and clean hydrogen is therefore critical



Clean hydrogen is essential for a net-zero world

Renewable power will have the greatest climate benefit when replacing coal in the power sector or gas for heating in connection with a heat pump (see Figure 25). This is due to efficiency. Between 20-30 per cent of the energy is lost in the conversion from renewable power to hydrogen. At the same time, the efficiency in coal and gas power is lower than in industry. Coal and gas power plants typically have an efficiency rate of 40-60 per cent in the power sector, while for gas in industrial processes this is often in excess of 90 per cent.

To cut emissions in the hard-to-abate sectors, it is urgently important to invest in clean hydrogen today without delay. It will take time to develop the hydrogen infrastructure and production capacity needed due to inertia in value chains, processes and expertise. The hydrogen value chain will need to be developed in parallel with realising the potential in the power sector and the heating sector so that green hydrogen can be scaled up quickly enough for the world to be on a global net zero emissions pathway.

Emission-free hydrogen is one of the few climate solutions to decarbonise parts of the industrial and transport sector.

8

Overview of transport and storage solutions for hydrogen

Due to hydrogen's low volumetric energy density, it needs to be packed more tightly during storage, either by compressing it to a higher pressure, cooling it until it becomes liquid or binding it chemically to another substance. Underground storage in geological formations is an attractive option for storing large volumes of hydrogen, but there is still uncertainty about which geological areas are most suitable. In general, we expect the following methods for storing clean hydrogen to be the most common, depending on volume and duration of storage:

- Due to the properties of the salt structure, converting existing underground salt caverns or building new ones on land seems to be the cheapest and technically best way to store large volumes of hydrogen over time, where this is possible. Europe has major potential for building and converting hydrogen salt caverns. Salt caverns are also relatively flexible in terms of how quickly hydrogen can be injected and withdrawn from storage.[68]
- Storing compressed hydrogen in a tank is flexible and is currently the most common storage solution, but costs can quickly escalate if large volumes need to be stored.

Other storage solutions are more immature or challenging in terms of technology, safety and leakage, and costs. This includes storage in underground mountain caverns, empty gas/oil reservoirs or empty mines, aquifers, and chemical forms of storage such as ammonia.

Transport: In general, we expect clean hydrogen to be transported in the following ways, depending on distance and volume:

Compressed hydrogen by truck for smaller volumes and distances

Hydrogen is compressed to 250-500 bar and each truck can carry 500-1,000 kg.

Compressing hydrogen gas requires 3-4 times more energy than fossil gas.

Smaller volumes can be transported using this method within a radius of approximately 500-600 km. The cost depends on fuel and labour costs, and to a lesser extent on the volume of hydrogen. For larger hydrogen volumes over longer distances, pipelines will be more cost-effective.

Compressed hydrogen via pipeline where this is available, for large volumes and a distance of up to 5,000 km

This is the main route how fossil gas is currently transported. Hydrogen is lighter than fossil gas (methane) and is transported almost three times faster through a pipeline, but its volumetric energy density is seven times lower. The same pipeline will therefore transport 20-25 per cent less energy with hydrogen than with fossil gas.

Pipeline materials will be made of stainless steel with a high corrosion resistance, or composite materials (newer, less common). The costs will be higher than for fossil gas and will depend to a large extent on the utilisation rate. A high utilisation rate will make this the most cost-effective way of transporting large volumes. A hydrogen pipeline network can be built by either converting existing fossil gas pipelines or building new ones at a slightly higher cost.

The hydrogen gas is compressed to approximately 70-100 bar and compressor stations are installed along the pipelines to offset pressure loss during transport.

In Europe, it is expected that a dedicated hydrogen infrastructure will be gradually developed as we approach 2050, and that this will facilitate regional hydrogen markets. This investment is capital intensive and will need political support and a policy framework. Regulations similar to those for fossil gas will be needed for safety, metering, ownership of infrastructure, etc

Hydrogen derivatives, such as green ammonia, are shipped for distances over 5,000 km

For longer distances between continents, we will probably see hydrogen transported by sea in the form of clean ammonia in the future. This method stores more energy per unit of space than liquid hydrogen and enables ammonia to be used directly, without converting it back to hydrogen.

Other options include using liquid organic hydrogen carriers (LOHCs) to bind hydrogen chemically to organic liquids or mixing hydrogen with magnesium that can be transported by sea. These solutions are relatively expensive and immature at the present time.

A 1.5°C pathway will require more renewables and electrification, and this must be implemented much faster.

Summary

In Statkraft's Low Emissions Scenario a strong dynamic between clean technology development and climate politics that can take us in line with a 2°C pathway, but not all the way to 1.5°C. Reducing emissions in line with a 1.5°C pathway will require further acceleration in political climate ambitions and the pace of global action. Every decimal that we can avoid is important.

A 1.5°C pathway will require more renewables and electrification, and this must be implemented much faster. In addition, it will be necessary to rapidly develop and commercialise new technologies, such as green hydrogen, to use renewable energy in sectors where direct electrification is challenging. Clean hydrogen is already an important climate solution in our Low Emissions Scenario and must be further scaled for a 1.5°C pathway. As we have seen in this report, the interplay between green hydrogen and the power market will be significant. In our Low Emissions Scenario, more than 10% of global power demand will come from green hydrogen in 2050 and more than 20% in Europe. Green, flexible hydrogen will produce more during the day and during the summer when the sun is shining. This will help absorb the increasing share of intermittent renewable power in the power systems. Thus, the mutual interdependence between green hydrogen, wind and solar power becomes substantial.

The recent IPCC report states that a 1.5°C pathway may still be possible but will require massive and rapid change. We have already seen a rapid development in the energy sector the last years, especially within solar-, wind power, batteries and electrolysers technologies. The Covid-19 pandemic has shown that prompt action can be taken when needed. A faster development than shown in our Low Emissions Scenario requires global cooperation and climate policies to not only facilitate, but also to actively push forward and accelerate the energy transition.

ANNEX 1:

Key parameters in the Statkraft's Low Emissions Scenario, compared with IEA and Bloomberg NEF[69]

Sectors	Statkraft's Low Emissions Scenario 2021	IEA STEPS (2020)	IEA Net zero (2021)	BNEF NEO (2021) Green Scenario
Annual growth in primary energy demand 2019-50	-0.2 %	0.82 %	-0.39 %	-0.38%
	Power sector			
Demand	2.7 %	1.91 % (til 2040)	3.19 %	5.07%
Wind power	8.4 %	6.60 % (til 2040)	9.66 %	13.5%
Solar power	11.7 %	10.6 % (til 2040)	12.2 %	12.4%
Hydro power	1.5 %	1.53 % (til 2040)	2.21 %	-
Fossil share in power sector (TWh, 2050)	16.1 %	44.5 % (til 2040)	0.36 %	0.00
	Primary energy			
Oil consumption: annual growth 2019-50	-2.70 %	0.31 % (til 2040)	-4.75 %	-5.91 %
Gas consumption: annual growth 2019-50	-0.06 %	1.23 % (til 2040)	-6.55 %	-6.06 %
Coal consumption: annual growth 2019-50	-2.74 %	-0.62 % (til 2040)	-12.0 %	-12.3 %
Global energy-related CO_2 emissions ($GtCO_2$) in 2050	14.7	33.3 (i 2040)	0.0	0.0

ANNEX 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 backward analysis from this.

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 fall then decreases 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 cooperation 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 in which 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.

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) are also excluded from the Low Emissions Scenario.

The emissions are broken down into the power sector, buildings sector, transport sector, industry sector:

- **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 within a national area, regardless of sector. This includes 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 here. Emissions from international transport are presented at an international level.
- **Industry:** Emissions in connection with the combustion and production of heat in the manufacturing and construction industries. The emissions include 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 are also included.

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