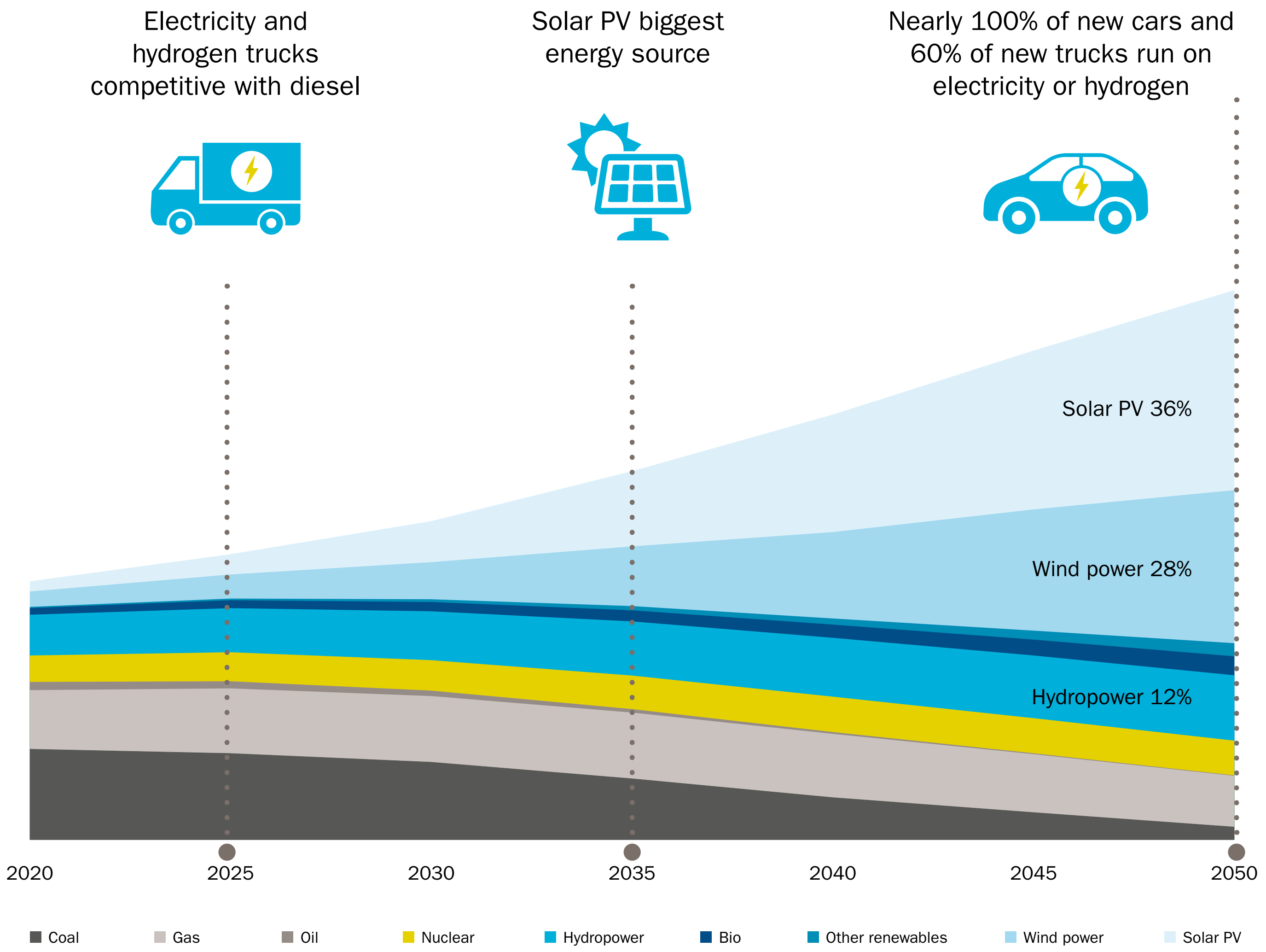
2019

Global energy trends

Statkraft's Low Emissions Scenario

Statkraft's Low Emissions Scenario 2019

The world must rapidly reduce emissions to meet climate targets. In the Low Emissions Scenario, the cost of solar PV will fall by 50% and wind power by 40% by 2050. A renewable power sector will make electricity increasingly attractive as a source of energy in transport, buildings and industry. This will result in 44% lower energy-related greenhouse gas emissions in 2050 compared to today, in line with a two-degree pathway. In 2050, natural gas will be the major source of emissions and the power sector will be 80% renewable.



Global electricity production towards 2050 (TWh)

Changes globally from today to 2050

x30 / x8
Solar PV/ wind power capacity

-60%
Cost for solar PV and batteries ***

Increased renewable energy

Increased electrification

Less fossil fuels

x2
Electricity demand

-43%
Oil demand

Lower emissions

More efficient energy use

x20
Electricity use in transport

-62%
Energy intensity **

-44%
CO_2 emissions *

* Energy related CO_2-emissions ** Primary energy related to GDP *** Solar PV with up to 6 hours battery

In 2050, wind power will meet almost 30% of the world's electricity demand. Photo: Getty Images/piola666

The energy world is changing

Overview of the Low Emissions Scenario

This is the fourth year in a row we present our Low Emissions Scenario. The scenario is based on an evolution of known technologies and assumes an optimistic and realistic continuation of current trends in renewable and clean technologies. In addition, the scenario assumes a political commitment to facilitating rather than hinder the energy transition, as well as adequate mobilisation of private capital. This means that market, technology and policy will reinforce each other and essentially move in the same direction. This year we have for the first time extended the time horizon for our analyses all the way to 2050 [1].

Energy systems are changing rapidly

The biggest change from last year is that we have once again adjusted our solar PV cost estimates downwards. This further intensifies the trends we outlined last year. In most countries, it is already profitable to install renewable capacity where *new* power is required. In the Low Emissions Scenario we see that in countries with good solar or wind resources, new renewable capacity will also soon be more profitable than *existing* coal or gas power.

The enormous drop in the cost of renewable energy is making it increasingly attractive to use electricity to decarbonise the industry, transport and building sectors. Areas that cannot be electrified directly can utilise renewable energy by using hydrogen as an energy carrier. In addition to observing a speedier transition in the power sector, the major changes since last year can be seen in the transport segment, where long-distance transport in particular is increasingly switching to electricity and hydrogen.

The outcome is a global energy system that differs fundamentally from the existing system, with sectors more closely integrated through electricity and hydrogen. Closer interaction between the sectors will reduce the need for fossil fuels further. As a result, demand for coal and oil will drop and the demand for gas will level off globally, resulting in a decline in energy-related greenhouse gas emissions.

We must do more of everything

In this year's Low Emissions Scenario, as in last year's, the global energy-related emissions are in line with a two-degree pathway. Energy-related emissions account for about three-quarters of global greenhouse gas emissions. In the past year, the 1.5-degree target became more relevant in the debate; this year we have therefore also analysed what is required for energy-related emissions to follow a 1.5-degree pathway. We did this by focussing in depth on the European energy system. The last part of the report shows that it is quite possible to follow a 1.5-degree pathway with continuing evolution of existing technology. The costs associated with this are likely to be far lower than the costs associated with the consequences of failing to achieve a 1.5-degree pathway. The biggest difference between the Low Emissions Scenario and a 1.5-degree energy world is speed. Both analyses describe the same solutions, but a 1.5-degree pathway requires much swifter action and the simultaneous development of several technological solutions.

Political will is crucial

Significant political will is required to achieve sufficient speed in the transition and thus limit global warming to 1.5 degrees. In recent years, climate policy has been strengthened in many countries throughout the world. However, climate and energy policy does not evolve in a vacuum. The Paris Agreement builds on countries working together and trusting each other meeting their obligations. Technology transfer, trade and mutual trust are all factors in meeting the global climate targets. Conflict and distrust make it harder to reach those targets. In recent years, we have seen tendencies towards lower levels of cooperation and more conflict. This may jeopardise a rapid and profound decarbonisation of the global economy.

[1] The Low Emissions Scenario builds upon Statkraft's own global and regional analyses and models, as well as in-depth studies from external sources. The scenario is not based on a linear projection of today's trends, nor does it base itself on a given climate target and perform a backward analysis from this.

Background: **Extreme weather, global climate engagement and fragmented policy measures**

Extreme weather has major consequences. Pictured here from Flåm in Norway where heavy rainfall made the river overflow its banks, causing severe damage. Photo: Tore Meek/NTB scanpix.

In the last year the series of strikes by school students, *Fridays for Future*, has grown into an international movement. This reached record levels when 1.4 million students went on strike on 15 March 2019. Companies, cities and countries are also moving climate change higher up on the agenda[2]. A number of European countries have set national targets for achieving climate neutrality, including Norway in 2030, Finland in 2035, Iceland in 2040, Sweden in 2045, and Denmark, France, the Netherlands, Portugal, Spain, the United Kingdom and Germany in 2050. Last year the European Commission launched its 2050 climate strategy; the strategy presents eight scenarios for transitioning the energy system. The strategy contains a vision for the EU – which is responsible for about 10% of the world's greenhouse gas emissions – to achieve climate neutrality in 2050.

We also observe that carbon pricing is being introduced in more countries and sectors. China and Mexico are gradually rolling out their national emissions trading systems, the Netherlands have opted to introduce a carbon price from 2020 and the EU's emissions trading system was reinforced over the past year. Globally, there are now 57 carbon pricing mechanisms in operation or scheduled for implementation. This covers approximately 20% of global greenhouse gas emissions and represents an increase of 11 initiatives since last year[3].

Global warming with visible consequences

Increased climate awareness is largely due to the consequences of global warming becoming more visible. We have already reached a global average temperature that is around 1°C higher than in

[2] C40 Cities (2019): https://www.c40.org, RE100 (2019): www.re100.org, We Mean Business (2019): www.wemeanbusinesscoalition.org, the Climate Group (2019): https://www.theclimategroup.org/ev100-members

[3] World Bank 2019. State and Trends of Carbon Pricing: https://openknowledge.worldbank.org/handle/10986/31755

pre-industrial times. The last four years were the warmest in history, and the effects of climate change are being felt in more and more areas. More species are threatened with extinction today than ever before in human history[4]. In 2018, greenhouse gas concentration in the atmosphere increased, sea levels continued to rise, and the sea surface temperature reached the highest levels to date. The extension of sea ice in the Arctic and Antarctic has dropped significantly below average. At the same time, oceans are becoming more acidic, causing drastic reductions in warm water corals.

Extreme weather also presents serious consequences. Natural disasters affected 62 million people in 2018. Floods affected 35 million people, while over nine million people were impacted by drought. Two hurricanes, Florence and Michael, hit the United States and caused USD49 billion in damage. After years of decline, extreme weather led to a global increase in famine.

In northern Europe, the record-breaking hot and dry summer last year led to major losses in food production, while 1,500 people died from the heat in France and 25 000 hectares of forest in Sweden were devastated by fires. Although there are complex causal relationships in each event, we know that man-made climate change increases both the magnitude and frequency of extreme weather[5]. Insurance companies were among the first to see the costs associated with climate change. Reinsurance company Munich Re warned in 2019 that insurance premiums for private individuals may become so high that insurance against climate change will become a social problem. Morgan Stanley estimated the cost of climate-related damages at USD650 billion for the period 2016-2018[6].

CHINA, THE UNITED STATES AND INDIA ARE THE WORLD'S TOP GREENHOUSE GAS-EMITTING COUNTRIES

China, the United States and India emit almost half of the world's greenhouse gases. Changes in these markets will have an enormous impact on emissions and the energy balance globally. The United States is moving from a net importer to net exporter of energy while gas and renewables are shifting coal out of the power mix. Coal power generation in the US is now at its lowest level in 30 years and accounts for 27% of the power mix.

At the same time, China is leading both in the production and consumption of renewable energy and is in the process of rolling out the world's largest emissions trading system. Serious problems with air pollution in many cities and the rising need for energy are important drivers for renewable energy investments. China already accounts for half of global demand for solar energy. Pollution in big cities has become a major health problem and has fuelled public engagement for cleaner air.

Parallel trends can be observed in India, home to eleven of the world's twelve most polluted cities. Here we see that growth in coal power is levelling off, with new installed capacity coming mainly from wind and solar power. The goal is to reach 100 GW of solar and 75 GW of wind power by 2022. In April 2018, India's prime minister Narendra Modi announced that all villages in India had been connected to the power grid. Since 2000, half a billion people have been given access to electricity in India. However, worldwide 840 million people remain without access to electricity[8].

Climate change affects countries differently

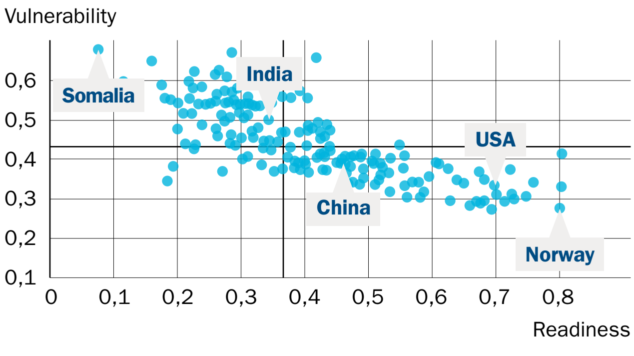


Figure 1: Poor countries are hardest hit by climate change.
Ranking of country vulnerability and readiness in 2017[7].

Greenhouse gas emissions increase for the second year in a row

In October last year, the UN Intergovernmental Panel on Climate Change released its special report on global warming of 1.5°C showing the serious climate consequences of a two-degree pathway compared to a 1.5-degree pathway[9]. The report also emphasised the high risk of exceeding the pathway periodically, unless rapid and drastic emission cuts are made in the next ten years. If emissions exceed the pathway, there is a risk of triggering irreversible climate changes, such as thawing of the Siberian tundra and melting of the Arctic ice. The report also shows that the impact of global warming is unevenly distributed, with India being one of the countries to be hit hardest by drought, heat waves and rising sea levels. These consequences will in turn affect food supply, food prices, migration and economic growth.

[4] The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019): https://www.ipbes.net/global-assessment-report-biodiversity-ecosystem-services

[5] World Meteorological Organizaion (2019): https://library.wmo.int/doc_num.php?explnum_id=5789

[6] Society of Actuaries (2019): https://www.soa.org/globalassets/assets/files/resources/research-report/2019/12th-emerging-risk-survey.pdf, Risk and Insurance (2019): https://riskandinsurance.com/cost-of-climate-change

[7] University of Notre Dame Global Adaptation Index (2018): https://gain.nd.edu/our-work/country-index/matrix

[8] World Bank (2019): http://documents.worldbank.org/curated/en/517781558037625254/Tracking-SDG-7-The-Energy-Progress-Report-2019

[9] IPCC (2018): https://www.ipcc.ch/sr15

Climate strikes by school students are creating momentum worldwide. Pictured here from a demonstration in Sweden, lead by the high-profiled climate activist, Greta Thunberg.
Photo: Liv Oeian/Shutterstock.com

Given the backdrop of more severe consequences from climate change, we still see emission levels are rising. Energy-related greenhouse gas emissions increased in 2017 and 2018 after three years of levelling-off. The main drivers of the emissions increase were economic growth and increased energy consumption [10]. Although Europe reduced its use of fossil energy sources and we are seeing a shift towards increased renewable energy globally, renewable energy is not growing strongly enough to offset the increase in energy consumption. Demand for gas, oil and coal rose worldwide, especially in Asia and the United States. This contributed to global emissions rising by 1.7% to 33 $GtCO_2$ in 2018.

Investment is being shifted from fossil energy to renewable energy

In 2018, for the third year in a row, more capital was invested in the power sector than in the oil and gas sector globally. Almost 2.5 times more capital is now invested in renewable energy than in fossil energy production. The major coal companies are diversifying away from new coal projects and there is a consolidation in the market. At the same time, insurance companies, banks and investment funds are withdrawing from investments in fossil energy sources. Goldman Sachs estimates that the main driver for coal companies dropping 60% in value over the past five years is that global investors are pulling out of investment in coal [11].

[10] IEA World Energy investments (2019): https://www.iea.org/wei2019

[11] Goldman Sachs (2018): https://www.goldmansachs.com/insights/pages/reports/re-imagining-big-oils-f/re-imagining-big-oils-report-pdf.pdf

[12] Oxford Institute for Enery Studies (2019): https://www.oxfordenergy.org/publications/energy-transition-uncertainty-implications-change-risk-preferences-fossil-fuels-investors/?v=c2f3f489a005

[13] Fossil free (2018): https://gofossilfree.org/wp-content/uploads/2018/12/1000divest-WEB-.pdf

A study from Oxford University shows that investors are demanding higher returns than previously to invest in major coal and oil projects; this is because of the increased risk associated with such investments. The study also shows that oil companies prioritise smaller and simpler projects, such as shale oil and maximising existing production, over major new development projects [12]. In 2018, over a thousand institutions committed to withdrawing their investments from fossil energy under specified criteria [13].

New renewable power generation covers almost half of the electricity growth. Installed capacity rose by 8% to 171 GW last year, of which new solar and wind power capacity accounted for 84% (108 GW and 50 GW respectively). At the same time, capital expenditure globally was flat. This is largely due to falling technology costs, especially for solar power. The relatively low growth rate for solar capacity compared to previous years (9%) was mainly caused by changes in the Chinese regulatory framework. On the other hand, high growth rates were seen in other regions, including Latin America which achieved 50% annual growth [14].

Electricity consumption rose significantly more than primary energy consumption, with increases at 4% and 2.3% respectively. Electricity demand increased more than overall energy growth because more people got access to electricity and the end users are electrifying away from fossil fuels. In 2018, two million electric cars were sold, corresponding to a 70% increase. 1.1 million of these were sold in China alone. As a result, there are now over five million electric cars in China. Europe constituted the second-largest market with 385,000 electric cars sold. The EU has defined new emission limits for passenger cars until 2030. A number of countries have adopted targets of phasing out the sale of fossil-fuelled passenger cars. Among the first are Costa Rica and Norway, with 2021 and 2025 defined as targets respectively, while Denmark, Ireland, the Netherlands and Sweden have set 2030; France and the UK have opted for 2040. China introduced an electric car quota for new car sales, stepping up from 10% in 2019 to 15% in 2025, corresponding to around seven million electric cars. India set a target for electric cars to make up 15% of new car sales in 2023.

Changes are also taking place in the other transport segments. Sales of electric buses grew by 32%, reaching 425,000 worldwide, of which 99% were purchased in China. At the same time, regulations and climate targets for the transport sector are being tightened at national, regional and global levels. After several years of negotiations, the International Maritime Organization (IMO) in 2018 set a target to halve greenhouse gas emissions from shipping by 2050 relative to the 2008 level, and this spring the EU agreed on emissions standards for trucks. Targets were also introduced for hydrogen use in transport. Fifteen countries globally have now introduced targets or support schemes for the use of hydrogen in road transport, including China, Japan and several EU countries [15].

The global political landscape creates uncertainty

In recent years, we have seen developments to indicate that the world is moving towards less cooperation. Political leaders advocating a more populist agenda have appeared in many countries in Europe and elsewhere in the world, indicating that many voters seek an alternative to the status quo. We see the same trends in energy and climate policy. While youth all over the world have protested *for* more ambitious policies, the yellow vests in Paris protested *against the consequences* of the same policies. Many populist parties in Europe have started to go *against* ambitious climate policies, arguing that the transition will be costly and lead to job losses [16].

Climate policies are becoming an issue that cuts across the traditional political dividing lines. A more fragmented political landscape in many countries may make it more difficult to reach broad and long-term compromises in climate policy – locally, nationally, at regional level and globally. An effective energy transition will require enhanced cooperation at all levels. If increased polarisation hinders workable compromises, this may impede achieving deep decarbonisation of the world economy. In contrast to this, we also see a strong shift of capital towards sustainable investments as a result of increased climate risk and the strong mobilisation among young people.

Trends towards fragmentation and polarisation in the political landscape globally. The Yellow Vest protest movement. Photo: Getty images/Bloomberg

[14] Bloomberg (2019), Global Wind Market Outlook Q119, Global Solar PV Market Outlook Q219: www.bnef.com, IEA (2019): https://www.iea.org/wei2019

[15] IMO (2018): http://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx, EU Clean mobility package (2018): http://europa.eu/rapid/press-release_IP-18-3708_en.htm
IEA (2019): https://www.iea.org/hydrogen2019

[16] WRI (2018): https://www.wri.org/blog/2018/12/yellow-vests-movement-isn-t-anti-climate-action-it-s-pro-social-justice

Hydropower will supply almost 12% of the world's electricity demand in 2050. Flexible hydropower has a unique ability to handle large variations in other renewable power generation and is an important solution to the world's climate challenges. Photo: Statkraft/Nils Lund

Global energy scenarios:
From fossil energy to renewable electricity

This chapter presents Statkraft's global Low Emissions Scenario out to 2050. The energy system is changing at a rate that was almost unthinkable just a few years ago. Onshore wind and solar power are expanding rapidly. The decline in costs for renewable technology and other key technologies, such as batteries and electrolysers, will impact the entire energy sector going forward. This chapter presents how the global energy system will transition, assuming that the growth trends we have seen in renewable technology in recent years continue over time. With emissions-free energy available at low cost in the power sector, electrification in sectors such as buildings, industry and transport become attractive climate solutions. Electrification will lower emissions and transform the entire global energy system.

Solar PV is the fastest growing energy source in the world and production increased by 25% last year[17]. A sharp reduction in the production costs of solar PV panels, relatively short project development time, and increasing demand for renewable energy mean that solar PV will grow faster than any other energy sources towards 2050 in the Low Emissions Scenario. Given this rapid growth solar PV is set to become the major source of power generation as early as 2035.

The decision to develop renewable energy will become even more attractive as solar and wind production costs gradually become cheaper than new coal and gas power projects in a growing number of locations. In addition to being a green alternative, renewable energy will also be the best option in economic terms. This will also make it easier to raise political climate ambitions, creating positive synergies between the market, technology and politics globally. In the Low Emissions Scenario, the world's electricity demand more than doubles by 2050, and renewable power generation increases more than six-fold. Growth in solar PV alone will cover two-thirds of all the growth in demand for electricity over the same period.

Solar and wind become the largest sources of energy and gas the major source of emissions

In the Low Emissions Scenario, primary energy grows by an average of 0.3% per year until 2050, as energy efficiency cannot fully compensate for the growth in population and economic growth[18]. This is significantly lower than the historical average growth of 2% per year from 2000 to present. In addition, we are already seeing a shift from fossil to renewable energy. Both coal and oil demand decline significantly. Nevertheless, the energy systems in 2050 continue to have a large share of fossil energy[19]. Electricity grows strongly in all sectors, on average more than eight times faster than primary energy towards 2050.

Global Primary Energy Demand
Billions toe

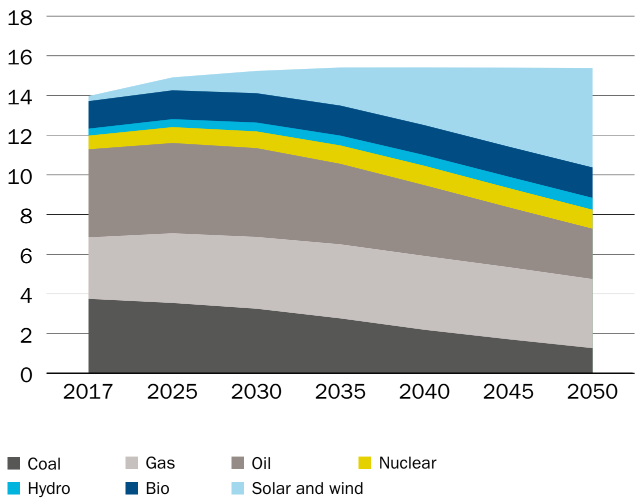


Figure 2. Global energy balance in primary energy from now until 2050. Low Emissions Scenario 2019.

Renewable power changes the premises for the energy systems

The Low Emissions Scenario sees a renewable share in the power sector globally of over 80% in 2050 where almost 70% of power generation is variable solar PV and wind power. Wind power will meet almost 30% of the demand for power in 2050, while solar PV will be the largest source of power generation from around 2035 and will meet close to 40% of power demand in 2050. By 2050, coal and oil will have been phased out almost entirely from the power sector; power from gas will also gradually decline.

[17] IHS Markit (Q1 2019): https://technology.ihs.com/609463/pv-installations-tracker-q1-2019, https://technology.ihs.com/609083/pv-module-supply-chain-tracker-q1-2019

[18] Primary energy refers to the direct amount of energy at the source that has not been subjected to any conversion or transformation process. While final energy refers to the energy consumed by end users, after conversion, transformation and distribution.

[19] The Low Emissions Scenario uses the IEA's calculation method. Primary energy calculations therefore take into account that much of the fossil energy is lost in processing and transport up to final consumption, while assuming zero loss for renewable energy. BP uses an alternative calculation method that assumes roughly the same loss for fossil and renewable power generation. Based on the BP approach, fossil energy will supply only around 30% of primary energy in 2050 instead of almost 50%. However, the absolute amount of fossil energy in the world will remain unchanged regardless of calculation method.

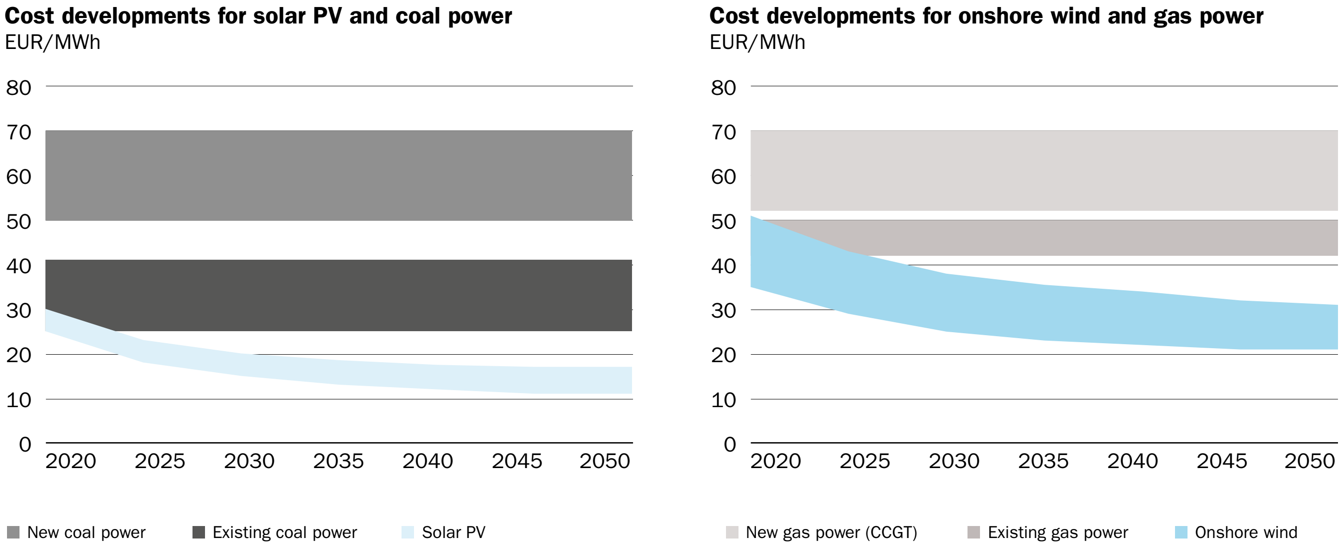


Figure 3. Illustration of expected cost developments for solar PV in sunny areas compared to new and existing coal power (left) and wind power in areas with good wind resources compared to new and existing gas power (right) in EUR/MWh. Low Emissions Scenario 2019.

An uncertain but crucial factor going forward will be the pace of technological development. Over the past two years, growth in renewable capacity was significantly slower than what is required to reach the two-degree target, not to mention the 1.5-degree target. In the Low Emissions Scenario, we are assuming a continued steep drop in the cost per MWh and a high rate of expansion until around 2030. After this, the decline in costs slows down somewhat, first for wind and then for solar energy (Figure 3). The range of possible outcomes is large. If the cost curve levels off earlier, it will take longer for renewable costs to fall and the expansion pace will be slower than the levels stated in the Low Emissions Scenario.

Wind power costs have dropped substantially and in large parts of the world it is already cheaper to build new wind farms than new gas or coal power plants (Figure 3). Turbines are larger, more efficient and more robust. They produce more power, require less maintenance and have a longer lifetime. Much of the technological development in recent years has been focused on areas with medium wind resources. An important driver for technological development is auction-based bidding systems where the developer with the lowest subsidy requirements wins the contract. In addition, developers have become more experienced and effective in implementing projects and in achieving better quality at all stages, including infrastructure. The wind technology manufacturers are becoming more globalised and consolidated.

We observe that the costs of building wind power plants are converging across geographic areas. Today, the ten largest wind turbine manufacturers cover 85% of the market.

In the Low Emissions Scenario, we expect an evolution rather than a revolution in onshore wind power technology, and the learning curve (cost trend as a function of installed capacity) will level off after 2030 as technology matures. Digitalisation of operation and maintenance also contributes to improvements. A large proportion of wind farms' operating and maintenance costs is affected by operating time. During hours with low electricity prices, wind power producers can respond to variable costs by adjusting production. This helps stabilise the production profile and may extend the lifetime.

If we assume that the lifetime of existing wind turbines is around 25 years, we will see an increasing renewal of old wind power plants towards 2040 and 2050. With the same capacity, the upgraded power plants will produce much more energy (TWh) as a result of technological improvements. In the next 5-10 years, we can therefore assume a tripling of installed capacity for each new turbine that replaces an old one. At the same time, less conflicts are expected around the renewal of old wind power plants than with the construction of new ones, as these are locations with wind turbines and infrastructure already in place. We estimate that roughly every fifth new turbine in 2050 is a renewal of an old turbine.

Solar PV grows faster than wind power since the technology is easier to develop, land area is not a limiting factor to the same extent as for wind power, and costs will generally be even lower than for wind. We have observed surprisingly steep cost reductions in recent years, with a drop in module costs of around 20% during 2018. Here too, auction-based bidding systems have pushed prices down. The lowest bids typically feature particularly positive underlying solar resources, short distances to the nearest transmission grid and low financing costs. Other decisive factors are local conditions such as tariff structure, auction rules and regulatory framework, local cost level, the solar PV share in the power mix and technological choices. It is expected that, for example, integration costs such as grid connection will increase in the future. When it comes to technology choice, we see an increasing use of mounting systems that follow the sun's position throughout the day (trackers). This also permits power generation during periods of lower solar intensity, giving a slightly flatter production profile throughout the day. This can partly offset the lower power prices during hours of high solar production. This may therefore be profitable in areas with abundant solar power, despite the tracking technology being a bit more expensive. Today, ground-mounted large-scale solar PV power plants cover approximately half of the solar PV capacity globally and this proportion is expected to increase somewhat in the future. We estimate that lifetime costs for solar PV and onshore wind power will fall by around 50% and 40% respectively towards 2050.

Eight times more wind power capacity and thirty times more solar power towards 2050

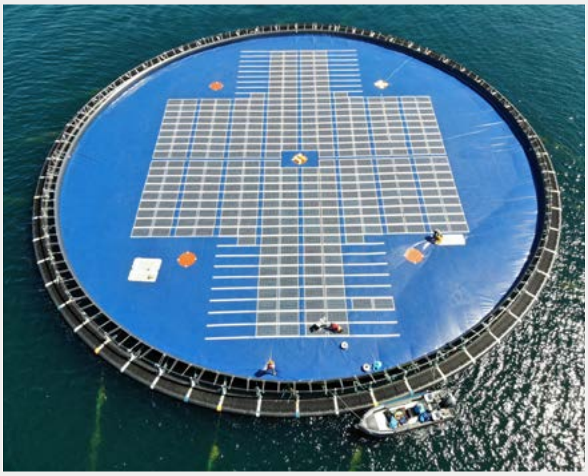
In the Low Emissions Scenario we estimate global volumes of around 14,000 GW of solar PV and close to 5,000 GW of wind power in 2050, corresponding to an annual electricity production of 21,000 TWh and 16,000 TWh respectively. We currently observe major variations in different countries' new build capacity. In China, 15 GW of wind expansion was delivered in one year, while India has so far only reached 3 GW in one year. In order to reach the volumes above, it will be important in the next few years to mobilise both the supplier industry and capital to support higher expansion capacity globally.

The volumes estimated in the Low Emissions Scenario are significantly lower than what is considered to be the global technical potential [20]. This is because growth could be dampened in some countries, for onshore wind power in particular, by alternative use of land areas, and local resistance.

Where there are restrictions on available land for onshore wind, we expect offshore wind to be an attractive alternative. The cost of bottom-fixed offshore wind has declined significantly in recent years, and in areas close to shore with good wind resources and shallow water, this technology can become competitive in the near future. There is uncertainty associated with floating offshore wind, although costs are expected to fall here as well. Currently, this technology is expensive when compared to both bottom-fixed offshore wind and especially onshore wind power and solar PV. We therefore expect countries that have alternatives to choose the more cost-effective solutions. However, in areas that have limited alternative resources, floating offshore wind will be more relevant. The volumes to be built in these areas are uncertain. The cost trend, which is highly dependent on the volume of global expansion, therefore also remains uncertain.

FLOATING SOLAR POWER ON EXISTING HYDROPOWER RESERVOIRS

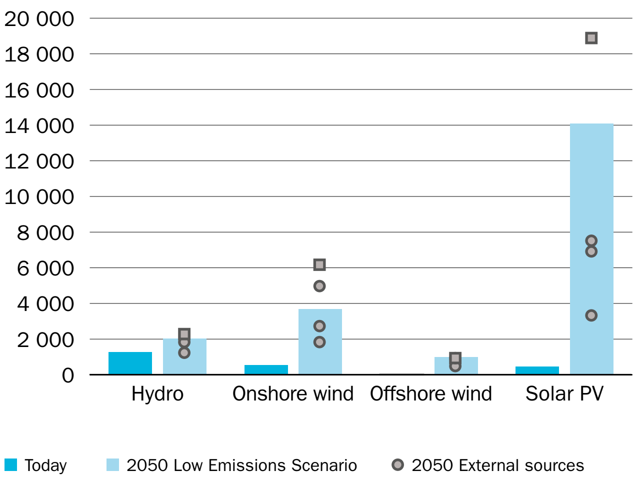
Floating solar power involves installing solar panels on floating structures on a body of water, such as a lake, fjord or ocean, or in a hydropower reservoir. If the plant is placed in a hydropower reservoir it can make use of existing infrastructure. The plant also reduces evaporation from the reservoir. There is tough competition on price in the market and finding cost-effective solutions is important. By the end of 2017, 0.25 GW of floating solar power was installed globally. This is expected to grow to around 10 GW by 2030. The volume will be considerably smaller than for onshore solar PV. To date, most of the existing floating solar plants are installed in Asia, where most of the growth is expected to continue, especially in countries such as India and South Korea.



Floating solar system, Statkraft plant in Albania. R&D project. Concept developed by Norwegian company Ocean Sun. This solution requires little material per kilowatt. Each unit basically consists of only a membrane, plastic floating rings and anchoring equipment, and the solar panels.

[20] Deng, Haigh, et. al (2015) estimate the technical potential in 2030 to be between 7 500 and 51 000 TWh for onshore wind power and even higher for offshore wind, and between 48 000 and 415 000 TWh for solar PV.

Renewable power capacity globally, today and in 2050
GW



Annual installations of solar PV
GW

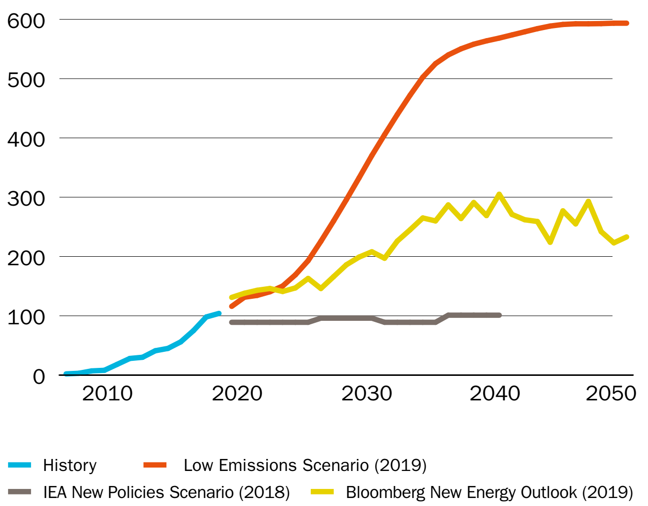


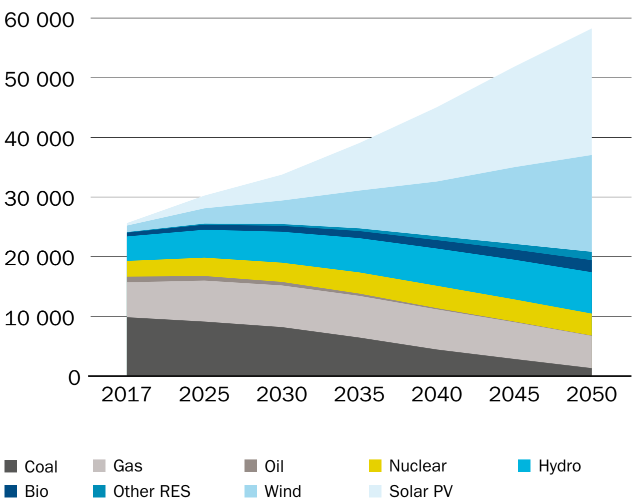
Figure 4. Renewable capacity today and in 2050 for the Low Emissions Scenario and external sources (left). Annual expansion of solar power capacity, per year (right).

Electrification will be the most important climate measure for buildings, industry and transport

There are generally five groups of climate measures available to reduce fossil energy use in the buildings, industry and transport sectors: 1) energy efficiency and circular economy, 2) electrification, 3) emission-free hydrogen, 4) carbon capture and storage or utilisation, and 5) bioenergy. As costs decline for renewable power, decarbonisation through electrification will become increasingly attractive.

In the Low Emissions Scenario, electricity becomes competitive with fossil alternatives in several segments in the industry, buildings and transport sectors. In a few years

Global electricity production
TWh



Electricity share of final energy use
%

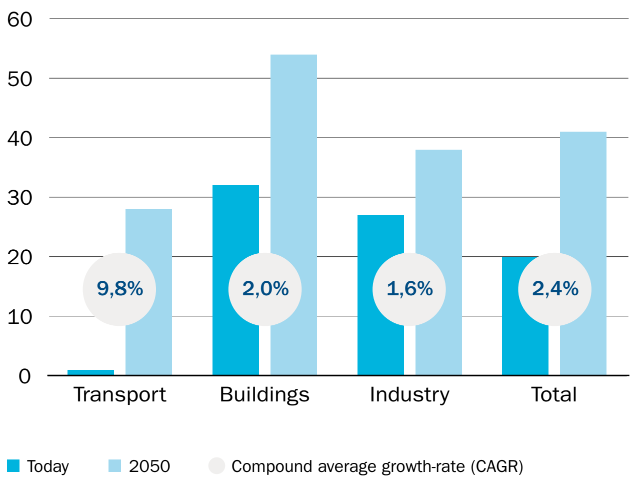


Figure 5. Electricity production to 2050 in TWh (left). The electricity share of final energy use per sector today and in 2050 and compound average annual growth rate per sector (right).

it will be cheaper to buy an electric car than a conventional car, excluding subsidies. – In addition, we expect support for infrastructure build-out.

The transport sector starts off with the lowest electricity share of final energy use at only one per cent today, but the growth rate to 2050 is much higher than for the other sectors. In the Low Emissions Scenario we achieve an electricity share of around 28% in the transport sector in 2050. With declining battery costs, increased political momentum and rapid adaptation by car manufacturers, we estimate that the transport sector will electrify faster than previously estimated. In the Low Emissions Scenario, we also assume that other segments such as trucks, trains and ships will follow suit. Battery-electric and hydrogen-powered vehicles with fuel cells are expected to be complementary solutions. In the Low Emissions Scenario, we estimate that the percentage of electric and hydrogen vehicles of new vehicle sales worldwide will approach 100% for passenger cars and 60% for heavier vehicles in 2050 [21]. In addition, we see a significant proportion of biodiesel and hybridisation in the heavy road transport and maritime sectors.

Passenger cars are expected to account for almost half of electricity consumption from transport in 2050, with heavy duty trucks and buses accounting for just over a third (Figure 6). Trains, ships and two-and three wheelers, make up the rest. This also includes a significant share of renewable hydrogen, primarily for heavier vehicles.

ELECTRIC CARS CUT EMISSIONS EVEN WHEN CHARGED WITH COAL AND GAS POWER

Driving electric and hydrogen cars is 100% emissions-free. The greenhouse gas emissions from electric cars come primarily from the power mix used to charge the car. The rest comes from the production of the battery, the car and the engine. Several studies have quantified the greenhouse gas emissions from electric cars compared to gasoline and diesel cars in a life cycle perspective. According to various studies, emissions from battery production may vary from 12 to 50g/km depending on the share of coal and gas in the power mix in the country where the batteries are manufactured. According to Statkraft analyses and studies by external researchers, charging an electric car from the average power mix used in Europe today means that the electric car will emit less than half the amount of greenhouse gases of a diesel car in a life cycle perspective [22]. With a clean power sector such as in the Nordic region and France, emissions are reduced by more than 80% compared to a diesel car. The power mix in Europe is becoming gradually greener as more solar PV and wind power is added to the mix. This increases the positive climate effect of switching from fossil to electric cars. On top of this, European power generation is regulated by the European emissions trading scheme [23]. This means that emissions from electricity used to charge an electric car are already within a pre-defined emissions cap, which is reduced annually. This is not the case with diesel and gasoline. This means that electric cars shift greenhouse gas emissions into the EU-capped emissions trading sectors while reducing emissions at the same time.

Share of total electricity use per transport segment in 2050
TWh

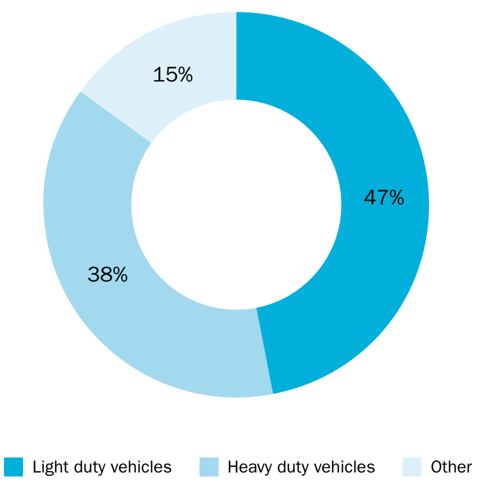


Figure 6. Electricity consumption by transport segment in 2050 including electricity for hydrogen use.

In the Low Emissions Scenario, the electricity share in *buildings* increases to 54% in 2050, up from today's 32%. This growth is primarily due to the switch from coal, gas, oil and bioenergy (wood burning) to electricity for heating and cooking. Electric heat pumps are particularly cost-effective heating solutions (see information box on page 16 on heat pumps). In addition, the demand for electricity in lighting, appliances and cooling is on the rise. Improvements in energy efficiency in both appliances and buildings will limit growth.

[21] We estimate that around 70% of the hydrogen for road transport will be produced by electrolysis and that hydrogen-powered and battery-electric vehicles will become complementary solutions in heavy transport. Local electrolysers located close to end use benefit from avoiding distribution and conversion costs.

[22] Emission factor of 300 gCO_2/kWh in the EU28 power mix in 2015. Metastudy of several life cycle analyses: around 120-205 gCO_2e/km for a diesel car compared with approximately 90-100 gCO_2e/km for an electric car driven for 200 000 kilometres. Transport & Environment (2017): https://www.transportenvironment.org/publications/electric-vehicle-life-cycle-analysis-and-raw-material-availability

[23] More about the European emissions trading scheme: https://ec.europa.eu/clima/policies/ets_en

HEAT PUMPS ARE IMPORTANT LOW-EMISSIONS ALTERNATIVES TO FOSSIL FUEL HEATING

Heat pumps use electricity and utilise ambient heat from the air, ground or sea to generate heat. The technology enables heat to be transferred from a lower to a higher temperature level. The heat energy is passed through an evaporator which increases the pressure and causes the heat energy to be converted into gaseous form. The hot gas then flows through a condenser which ensures that the heat is transferred to tap water, water-borne heat or indoor air.

Heat pump sales reached a record high of 16 million units globally in 2018, up 18% from 2017. In Europe, heat pump sales increased by 12% last year and cover around 10% of the European heating sector.

Heat pumps can produce three to four times more heat than traditional heaters with the same energy use. Even a heat pump using electricity from 100% coal power will account for less or the same amount of greenhouse gas emissions as a highly-effective gas boiler operating at 90% efficiency. Methane leaks from the gas distribution network are not included. Within buildings, heat pumps are thus important for both energy-saving and the climate, even in countries with a high share of coal in the power mix. Further growth globally depends on regulatory frameworks as a heat pump costs more to buy than a gas boiler[24].

Within the *industry* sector, electricity, hydrogen, energy- and material efficiency and some bioenergy partly replace the use of fossil fuels. Industrial heat currently accounts for 15% of global greenhouse gas emissions, and more than half comes from the steel, cement and chemical industries. For industrial processes that require low heat, electrification is a cost-effective solution. In the Low Emissions Scenario, the share of electricity in final energy will rise from today's 27% to 38% in 2050. At the same time, we see that hydrogen becomes more important, especially after 2040.

More details on climate solutions in transport, buildings and industry are described in the next chapter.

More complex interaction between the sectors and hydrogen will play a role

One consequence of electrification is that all energy sectors are more closely integrated than they have been historically. The closer interdependence of the power, industry, transport and building sectors is referred to as sector *coupling*. Such interconnection of the sectors has major consequences for the power market.

Historically, the energy landscape has been dominated by the direct use of coal, oil and gas with a smaller role for electricity. Looking forward, the power sector will become increasingly pivotal. In addition to the growing demand for power from electrification, sector coupling will provide valuable flexibility to the power system and various forms of energy storage.

Some areas are less suitable for direct electrification. A cost-effective solution for several applications will thus be converting electricity into *emission-free hydrogen*. In the Low Emissions Scenario, we see a gradual increase in the global demand for hydrogen. This will primarily be in the transport sector, but also to some extent in industry. Hydrogen use in the heating sector is set to rise after 2040.

Hydrogen from renewable electricity will be an important solution to decarbonise a range of sectors. Renewable hydrogen will affect the power market in multiple ways. The cost of hydrogen production from electricity varies with the electricity price and the electrolyser's utilisation rate. Optimal hydrogen production will therefore balance operating hours with electricity price variations. Flexible operation of electrolysers can add value to the grid. To make best use of this flexibility, the electrolyser's value to the grid should be reflected in the tariffs. Hydrogen can also be converted back into power using fuel cells or gas turbines for extended periods with low wind or solar PV production. This is considered a relatively expensive flexibility solution and our analyses therefore indicate that hydrogen use converted back to power will be small relative to hydrogen use in other sectors. Hydrogen as a climate solution is discussed further on page 25.

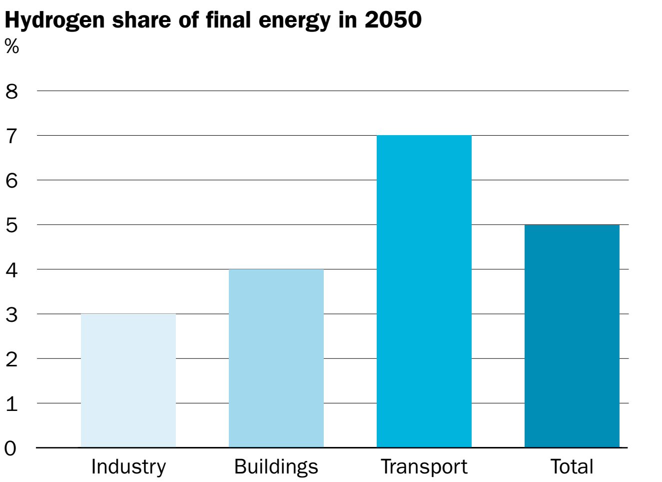


Figure 7. Global hydrogen share of final energy per sector in 2050. Low Emissions Scenario 2019.

[24] NOVAP (2019): https://www.varmepumpeinfo.no, IRENA (2019): https://www.irena.org, IEA (2019): https://www.iea.org/wei2019

EMISSION-FREE HYDROGEN WILL PLAY A ROLE IN DECARBONISING THE ENERGY SECTORS GLOBALLY

Hydrogen is the dominant element in the universe and the simplest atom in the world. Most of the hydrogen on earth is chemically bound to other elements, most commonly in the form of water. Hydrogen gas is colourless, odourless and tasteless.

The first electrolyser in Norway was installed by Norsk Hydro in Notodden in 1927 for use in fertiliser production. Approximately half of the world's hydrogen production of around 70 million tonnes a year is today used to make ammonia, while about one quarter is used in refineries.

The two most common methods of producing hydrogen are with electricity and water via electrolysis or with fossil gas via steam methane reforming (SMR). With renewable electricity, hydrogen is called "green", while hydrogen from fossil gas via SMR is called "grey". By adding carbon capture and storage to the SMR plant, emissions can be reduced by approximately 90%; such gas is designated "blue" hydrogen. There is great uncertainty linked to the cost of blue hydrogen and the timeline for when such plants can come into operation.

Green hydrogen is 100% emission-free, is produced in smaller modules and is therefore suitable for local applications, with production close to the point of demand. Blue hydrogen is produced in large units centrally and can potentially use existing natural gas infrastructure for distribution. Future energy systems will most likely consist of a mix of the two sources, depending on the availability of natural resources, infrastructure and demand in the area, as well as cost developments for the technologies.

Since the chemical reaction between hydrogen and oxygen gas is explosive, handling requires professional safety rules that should be standardised internationally. Strict safety rules also apply to other fuels such as gasoline and diesel.

Due to its low energy density per volume, hydrogen gas requires a lot of storage space. The gas must therefore be compressed and converted if it is to be transported or stored in larger volumes. By switching from compressed hydrogen in gaseous form (700 bar) to liquid form, less space is needed for the same amount of energy as the energy density more than doubles. However, handling liquid hydrogen is challenging as it requires a temperature of -253°C. Other hydrogen carriers such as renewable ammonia and methanol have volumetric energy densities three times higher than hydrogen in compressed form (Figure 8). Their chemical properties mean that conversion from hydrogen to methanol and ammonia may be advantageous for certain applications, for example, long-distance shipping.

Energy density by volume and weight

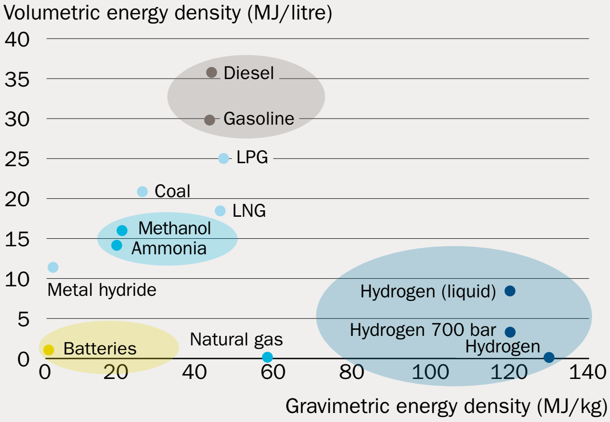


Figure 8. Energy density for different energy sources (in volume and weight).

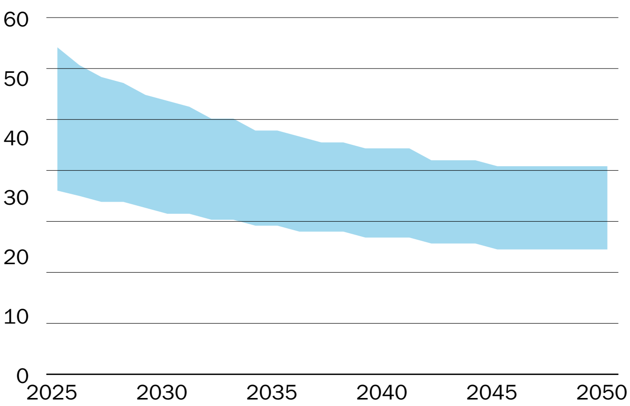
Enhancing system flexibility in a weather-dependent power system

Changing weather conditions cause large fluctuations in the production of solar PV and wind power. This makes integration into the power systems difficult. Solar PV and wind power are called variable energy sources as they only produce electricity when the sun is shining, or the wind is blowing. A high share of solar PV or wind power in the same market without enough flexibility [25] pushes down the market price and affects the profitability of the investment ("cannibalisation effect" [26]) . Once the world can store and use electricity from the sun and wind more efficiently, the transition will accelerate. As the need for flexibility in Europe increases, Norwegian hydropower can be one of the economically most attractive alternatives to meet the long-term flexibility needs and thus contribute to the decarbonisation of our neighbouring countries. In our analyses, the power system manages to handle above 70% variable renewable power. Even though technology costs for solar PV and wind power will decline, we expect the costs of integrating variable power into the power system to rise in parallel with the higher share of variable solar PV and wind power in the power mix. This relates particularly to costs of grid expansion and flexibility. How the costs will be distributed between the producer, consumer and grid owner will vary for different regions. Increased integration costs can offer incentives for innovative solutions and technology improvements. We expect, among other things, that investors will put together more combinations on the production side, evening out the production profile ("production flexibility"). Examples include solar PV combined with wind power, solar PV in combination with batteries, and renewable power generation paired with hydrogen production. In countries with good solar resources, such as India, batteries together with solar PV production may be an excellent combination as it permits storing of electricity for the evening and night.

[25] *Flexibility* is the ability to make quick changes in production or consumption at any time to ensure balance in power systems. This can be anything from an instantaneous change in effect over seconds and minutes (load regulation) to the balancing of power systems for extended periods, days or weeks, e.g. during longer periods of low wind.

[26] *Cannibalisation effect* means that the profitability of renewable, variable power decreases as more similar power is added.

Cost developments for solar PV and batteries (USD/MWh)
USD/MWh



Costs (high and low) for converting green hydrogen back to power
EUR/MWh

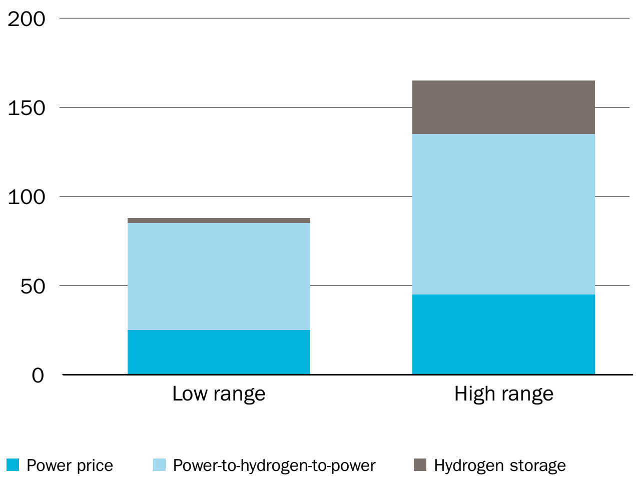
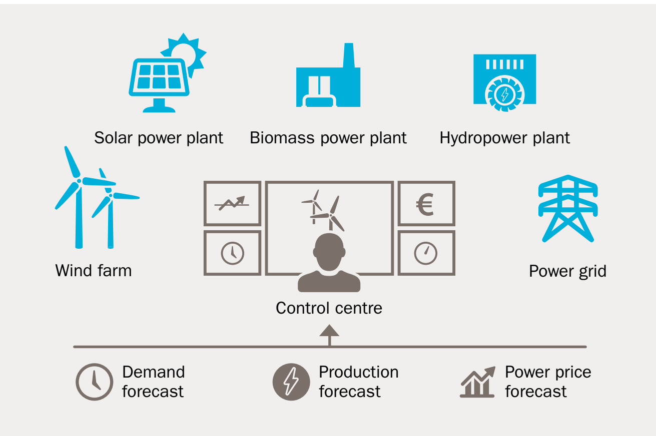


Figure 9. Illustration of cost developments for solar PV combined with batteries in sunny areas and up to four hours' storage (USD/MWh) (left). Costs (high and low) for renewable hydrogen converted back to power via fuel cell plant in 2030 (EUR/MWh) (right). Low Emissions Scenario 2019.



Statkraft operates Europe's largest virtual power plant of 12 000 MW in Germany.

The main challenge in European markets will be a need for long-term flexibility over days and weeks. Long-term flexibility solutions are currently offered by gas power, coal power, bioenergy, hydropower, cables, or longer demand response from industry. Flexible hydropower is one of few renewable solutions that can provide both short- and long-term flexibility. Hydropower can quickly adjust production and has low start and stop costs. Where it is possible, expanding the power capacity of hydropower will be one of the most economically attractive options to cover long-term flexibility needs. Over time, coal power will be phased out, while gas is gradually replaced by, among other energy sources, emission-free hydrogen. In a 1.5-degree pathway, Europe can achieve 100% emissions-free power production (see next chapter).

INTEGRATION OF VARIABLE SOLAR PV AND WIND POWER USING VIRTUAL POWER PLANTS

There are numerous ways to increase flexibility in the power system to integrate a higher share of variable power production from solar PV and wind. The optimal mix of flexibility solutions will depend on local conditions. We expect that the various energy markets and power systems will require all of them. Broadly speaking, the flexibility solutions can be categorised into i) production and demand flexibility, ii) flexibility in the physical power system (smart grids and cables), iii) flexible market solutions (better intra-day trading across borders, trading closer to real-time, etc.), and finally, iv) flexible business models [27]. Virtual power plants are an example of a flexible business model:

Understanding the weather becomes more important when producing and trading with renewable energy and there is flexibility in controlling several solar PV and wind power plants in different locations as a portfolio. Even five minutes before selling the production from a wind farm, you do not know exactly how much you will produce. For example, by remotely controlling multiple power plants, the production rate of a power plant can be lowered if there is sudden excess power and prices drop. In this way, virtual power plants can balance production and limit surplus production. This can be combined with, for example, flexible industry consumption, flexible electrolysers and storage solutions such as batteries.

[27] Statkraft's Low Emissions Report 2018 describes various flexibility solutions in greater detail: https://www.statkraft.com/globalassets/explained/statkrafts-low-emissions-scenario-report-2018.pdf

Demand for fossil fuels is declining

With renewable power production and increased electrification, the demand for fossil fuels and resulting greenhouse gas emissions will decline globally. Demand for oil is primarily falling due to electrification of transport, but also because of lower demand from industry and buildings. Oil will be completely phased-out in the power sector. The biggest consequences are observed in the coal industry, with a two-third demand drop from current levels over the period. The global gas sector will also be impacted by the energy transition. Gas demand will rise slightly until 2040 in the Low Emissions Scenario and will then begin to decline towards 2050. When looking at energy-related CO_2 emissions, natural gas will be the largest source of emissions globally in 2050. Oil will overtake coal around 2040 as the largest source of emissions, only to be overtaken by gas around 2045. The growth in clean technologies and the market trends that we assume in the Low Emissions Scenario results in energy-related CO_2 emissions falling by 44% from today's levels, consistent with a two-degree pathway towards 2050 (Figure 12). However, this is not enough. To follow a 1.5-degree pathway, the solutions outlined in this chapter must be implemented faster and the transition must be even more extensive. This will have major implications, especially for natural gas, which is largely replaced with emission-free solutions in our analyses. We will take a closer look at this in the next chapter.

Demand for oil, coal and gas
Indexed from 2017

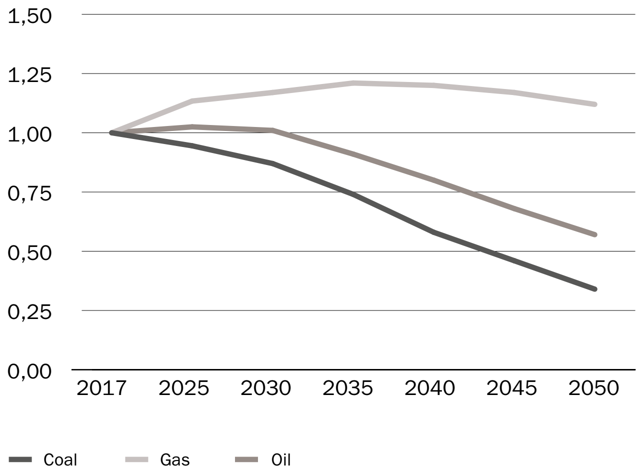


Figure 10. Demand for oil, coal and gas indexed from 2017 (primary energy). Low Emissions Scenario 2019.

Demand for coal declines by two-thirds to 2050. Coal transport in open train cars, Kentucky, USA. Photo: Getty Images/tinabelle.

°CICERO

Emission pathways consistent with 1.5°C

Guest article by Glen Peters, Research Director, CICERO

The Paris Agreement sets two important climate goals. The first climate goal is to keep the temperature increase well below 2°C and pursue effects to limit the increase to 1.5°C (Article 2). The second climate goal is to achieve a balance between emissions by sources and removals by sinks of greenhouse gases in the second half of this century, meaning achieving net-zero greenhouse gas emissions between 2050 and 2100 (Article 4). A 1.5°C temperature limit is preferable for climate impacts but increases the mitigation challenge. The climate is affected differently by long-lived greenhouse gases like CO_2 that have a cumulative impact for centuries, and short-lived greenhouse gases (like methane and sulphur dioxide) where the climate effects may dissipate over decades. As a consequence, not all scenarios require net-zero GHG between before 2100, but they do require net-zero CO_2 emissions before 2100.

More than hundred different *1.5 °C pathways* have been generated by different Integrated Assessment Models using different socioeconomic and technology assumptions. The 'Shared Socioeconomic Pathways' (SSPs) allow analysts to explore the consequences of different socioeconomic assumptions on mitigation (e.g., population, political challenges). Different models have different technology costs, dynamics, and interactions, leading to different energy systems.

All 1.5°C and 2°C scenarios have some similar characteristics, but with differing details. Broadly, 1.5°C scenarios require a 50% reduction in CO_2 emissions by 2030, net-zero CO_2 emissions by 2050, and large-scale CO_2 removal. All the 1.5°C scenarios require a rapid decline in the use of unabated fossil fuels and a rapid rise in the use of non-fossil energy sources, though the relative declines of coal, oil, and gas, or growth of solar and wind, may vary. All models require CO_2 removal, but models may use different amounts and technologies: natural approaches include afforestation and engineered approaches include bioenergy with carbon capture and storage. While CO_2 emissions become negative after 2050 in nearly all scenarios, non-CO_2 greenhouse gases may not. The relationship between CO_2 and non-CO_2 emission reductions depends on technology options and costs in different models.

IPCC Special Report on 1.5°C of Global Warming profiled four scenarios consistent with 1.5°C. Three of those scenarios that do not exceed 1.5°C, or with limited overshoot, are shown in figure 11 (below). Each scenario contains different socioeconomic and technology assumptions. Figure 11 shows the main characteristics of 1.5°C scenarios across the elements CO_2 from fossil sources, CO_2 from land-use change, non-CO_2, and CO_2 removal.

Statkraft Low Emissions Scenario focuses on CO_2 emissions from fossil sources (the grey area in the graph). However, the climate is also affected by land-use change (yellow area), CO_2 removal (green area), and non-CO_2 greenhouse gases (light blue area). The temperature response also depends on air pollutants, like black carbon and sulphur dioxide, but they are not shown in this figure.

Greenhouse gases from *non-CO_2 sources* (CH_4, N_2O, SF_6, HFCs, and CFCs) are often harder to mitigate than many CO_2 sources. CH_4

Global Greenhouse Gas Emissions
CO_2-eq

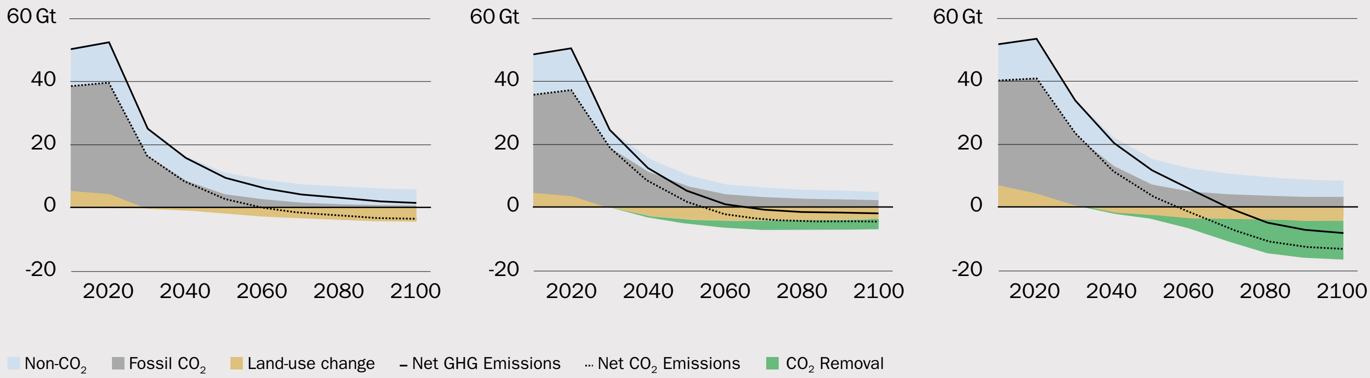


Figure 11: Three characteristic 1.5°C scenarios showing the importance of a massive reduction in fossil fuel emissions (grey) and a shift from deforestation to afforestation (yellow). Source: IPCC Special Report on 1.5°C of Global Warming.

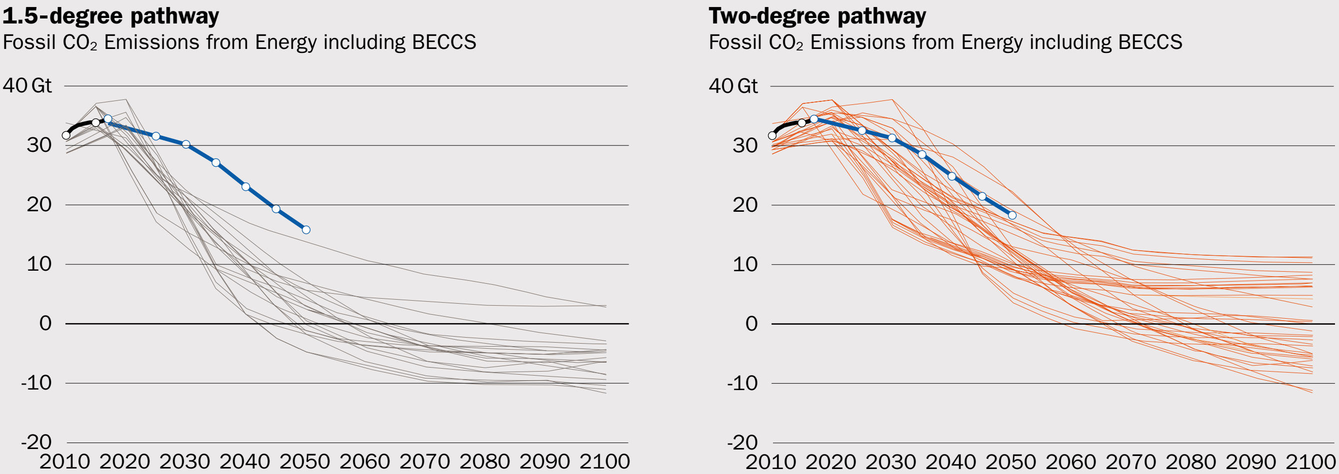


Figure 12: The Statkraft Low Emissions scenario (blue line) shown in comparison to the fossil CO_2 emissions from energy in 1.5°C scenarios with no or limited overshoot (left) and 2°C scenarios (right) where data is available [28]. Including fossil CO_2-emissions and bioenergy with carbon capture and storage.

and N_2O are often from diffuse agricultural or fossil sources, but they can still be reduced significantly (e.g., eating less meat, fixing natural gas leaks). 1.5°C scenarios typically have non-CO_2 greenhouse gas reductions of 30% by 2030, 50% by 2050, and 60% by 2100. Some scenarios have much more aggressive non-CO_2 reductions towards zero emissions as early as 2050, allowing slightly higher CO_2 emissions from fossil or land sources or less CO_2 removal.

About 10% of current greenhouse gas emissions are from *land-use change*, primarily from cutting down of trees (deforestation). By 2030, nearly all 1.5°C scenarios increase forest area by reducing deforestation and planting trees (afforestation). Net afforestation essentially translates into increased forest area, protection, and management, and can become a net sink of between 0 and 5 billion tonnes CO_2 per year depending on the scenario. Afforestation is a form of large-scale CO_2 removal, though it can lead to land, water, and biodiversity impacts.

Nearly all 1.5°C scenarios use large-scale engineered *CO_2 removal*, mainly by combining bioenergy with carbon capture and storage. Bioenergy with carbon capture and storage transfers carbon from the atmosphere to biomass through growth, but when the biomass is used for energy production the CO_2 is captured and then stored. Most scenarios start deploying these technologies in 2020, with the most ambitious scenarios reaching around 5 billion tonnes CO_2 removal per year by 2050 and 10 billion tonnes CO_2 removal per year by 2100. There are other forms of engineered CO_2 removal, such as directly removing CO_2 from the air, but these technologies are not implemented in most models.

Statkraft Low Emissions Scenario is primarily about *fossil CO_2 emissions* from the energy sector. These emissions drop rapidly in most 1.5°C scenarios, but only a few scenarios reach zero fossil fuel CO_2 emissions in the energy sector. This is because some sectors are hard to mitigate, such as long-distance transport and metals production. After 2050, fossil CO_2 emissions from energy could be between 0 and 5 billion tonnes CO_2 per year, depending on the model, with values up to 10 billion tonnes CO_2 per year possible in 2°C scenarios. When linked to bioenergy with carbon capture and storage, many of these scenarios still reach net-zero CO_2 emissions.

Figure 12 shows yearly energy-related CO_2-emissions in the Statkraft Low Emissions Scenario (blue line) together with a range of individual 1.5°C scenarios (left graph) and 2°C scenarios (right graph). The scenarios include fossil CO_2-emissions and bioenergy with carbon capture and storage. As the figure shows, the Statkraft Low Emissions Scenario is clearly more consistent with the range of 2°C scenarios (right).

[28] Scenario data fra: IAMC 1.5°C Scenario Explorer hosted by IIASA (release 1.1) https://data.ene.iiasa.ac.at/iamc-1.5c-explorer, analysert i Rogelj, Shindell, et al, Mitigation pathways compatible with 1.5°C in the context of sustainable development, in «Special Report on Global Warming of 1.5°C (SR15)», Intergovernmental Panel on Climate Change, Geneva, 2018: http://www.ipcc.ch/sr15

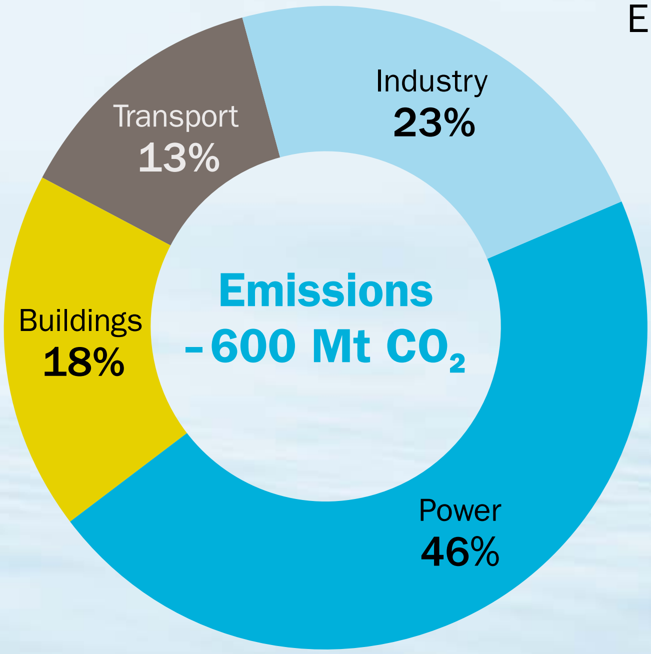
Changes from the Low Emissions Scenario (two-degree pathway) to 1.5-degree pathway for Europe:

+25%

Km transported with electricity or hydrogen

+20%

Electricity demand in industry



+14%

Households using hydrogen in heating

+19%

Renewable power production

Wind power +28%
Solar PV +14%

+27%

Cross-country interconnectors

+11%

Power demand

The graph shows the percentage of emissions reductions per sector from a two-degree pathway to a 1.5-degree pathway in Europe. Statkraft analysis.

Solutions to reach a 1.5-degrees pathway

The previous chapter showed that the global energy-related emissions are in line with a two-degrees pathway in a Low Emissions Scenario. However, to limit emissions in line with a 1.5-degrees pathway, the transition must occur at a much faster pace. According to the IPCC, this would mean halving the remaining carbon budget compared to a two-degree pathway [29]. In this chapter, we take a closer look at what is needed for a 1.5-degree pathway compared to a two-degree pathway for Europe. We assume that the 1.5-degree target will be met and explore what implications this has for the European energy system relative to a Low Emissions Scenario.

The conclusion is that following a 1.5-degree pathway for the energy sector is challenging, but possible. The solutions exist and implementing comprehensive and rapid measures is likely to be significantly cheaper for the world than the alternative – doing less. The solutions outlined for Europe will also be relevant for countries in other regions, but the speed and share of emission reductions from the different solutions will vary [30].

All energy sectors must cut emissions quickly

At global level, the emissions gap between the Low Emissions Scenario and the average of IPCC 1.5-degree pathways is approximately 16 $GtCO_2$ in 2050. In addition, all the 1.5-degree scenarios assume lower global energy-related CO_2 emissions towards 2050 than the Low Emissions Scenario (Figure 12, CICERO). This shows the need for further emissions cuts in order to reach the 1.5 degrees target. There are large variations in emissions in the various 1.5-degree scenarios, depending on the combinations, scope and implementation timeframe of the solutions chosen. For example, different levels of CO_2 removal and carbon capture and storage are used. In all the global scenarios, the use of fossil fuels declines significantly and the carbon intensity in the power sector approaches zero (Figure 12). All scenarios assume aggressive emissions cuts after 2050, and from other greenhouse gases such as methane. (For more details, see pages 20 and 21, CICERO).

Experts estimate that in order to follow a global emission pathway of 1.5°C, the EU must cut its greenhouse gas emissions by between 90% and 100% in 2050 compared with 1990 levels (See information box on page 24 for more details). To better understand how the European energy systems could meet a 1.5-degree target, we applied an energy systems model to analyse the different sectors in more detail [31].

In our analyses, we have assumed emission cuts of 95% in the European energy sector by 2050. This gives a completely emissions-free power sector. Figure 13 shows how emissions must decrease as of today in all sectors to follow a 1.5-degree pathway. This results in further emission cuts of 600 $MtCO_2$ in 2050 compared to the Low Emissions Scenario.

Energy-related CO_2 emissions in Europe

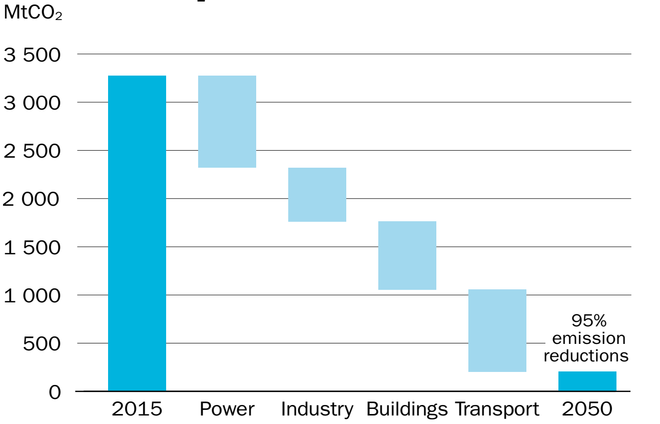


Figure 13. Emission cuts in Europe from today until 2050 in a 1.5-degree pathway (in $MtCO_2$).

[29] IPCC's latest 1.5°C report (https://www.ipcc.ch/sr15) contains updated carbon budget estimates with approximately 1170 $GtCO_2$ outstanding for a 66% chance of limiting the temperature increase to below 2°C in 2100 and about 580 $GtCO_2$ for a 50% chance of limiting temperature increase to 1.5°C in 2100. Updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to the previous IPCC report (AR5).

[30] Among other things, energy demand will have to increase significantly in several countries globally to achieve the sustainability goals, while energy demand is expected to decline in Europe. There are still three billion people in the world without access to clean cooking facilities and 840 million without access to electricity. IRENA (2019): https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

[31] The model is based on GENeSYS-Mod developed by Technische Universität Berlin ("Designing a Model for the Global Energy System — GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)" by Konstantin Löffler, Karlo Hainsch, Thorsten Burandt , Pao-Yu Oei, Claudia Kemfert, and Christian Von Hirschhausen (2017).

All sectors must bear their share of the extra emissions cuts. Statkraft's energy system model assumes that the least cost solutions are chosen. Cost optimisation is applied across regions and sectors. According to the model analysis, a cost-effective transition of the energy systems in Europe results in the power sector contributing 46%, industry 23%, buildings 18%, and transport 13% of the 600Mt extra emission cuts in 2050. However, alternative burden sharing across sectors are also possible. The EU Commission's 2050 climate strategy includes two different 1.5-degree trajectories where the first primarily explores a variety of technological solutions and the second relies on significant lifestyle changes [34].

Electrification is essential to achieve a 1.5-degree pathway

As mentioned in the previous chapter, there are roughly five main solutions to reduce energy-related greenhouse gas emissions: energy efficiency and circular economy, electrification and a decarbonised power sector, emission-free hydrogen, carbon capture and storage or utilisation, as well as bioenergy. Statkraft's analyses show that electrification along with improvements in energy efficiency are the most important means of moving from the Low Emissions Scenario to a 1.5-degree pathway. Electrification accounts for over 80% of the additional emission cuts required in the transport sector, while in the buildings and industry sectors, electrification accounts for around half (Figure 14).

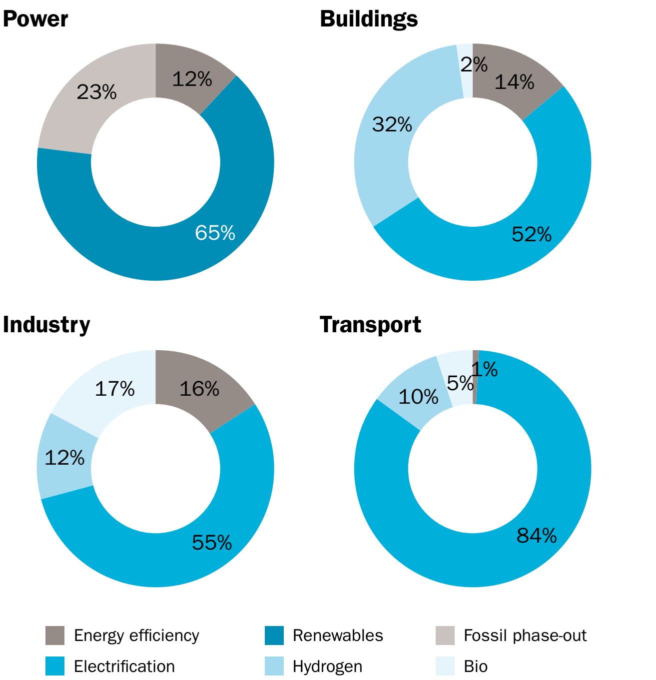


Figure 14. Cost-optimal decarbonisation per sector in Europe in line with a 1.5-degree pathway from today until 2050. Industry emissions include direct energy consumption and not feedstocks. Statkraft analyses.

The EU accounts for around 10% of the world's current greenhouse gas emissions. Photo: Getty Images/77studio.

THE EU'S SHARE OF GLOBAL GHG EMISSIONS REDUCTIONS FOLLOWING A 1.5-DEGREE PATHWAY

In October 2018, the European Commission presented its strategy for a carbon-neutral Europe. With this non-binding strategy, the EU may be among the first to reach the goal of net-zero emissions in 2050. The strategy is now under negotiation with the member states and the European Parliament. The strategy contains a number of different scenarios for emission cuts towards 2050.

Several recent studies estimate that to be consistent with a two-degree pathway, EU countries must cut their greenhouse gas emissions by 80% in 2050 relative to 1990 levels. To achieve a global 1.5-degree pathway, external studies show that the EU must reduce its emissions by 91-96% compared with 1990 levels by 2050 [32]. To follow a 1.5-degree pathway, experts estimate that the world must reach net zero CO2 emissions well in advance of 2100 (see page 21 and 22, CICERO). The different analyses contain significant uncertainties, including the effect of critical tipping points and the effect on global warming from other greenhouse gases. Several analyses therefore recommend that the EU should reach net zero greenhouse gas emissions by 2050 and that rapid emission cuts will increase the probability of limiting global warming and will be less costly than delaying [33].

Powermix in Europe
% of TWh

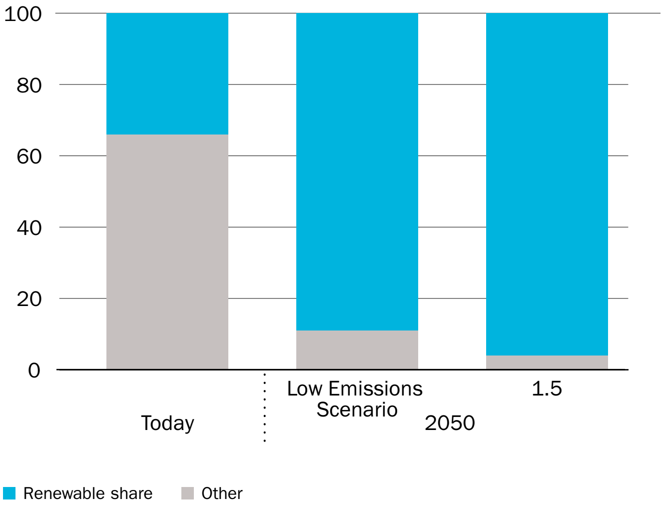


Figure 15. Power mix in Europe in the Low Emissions Scenario and 1.5-degree pathway, % of TWh. Statkraft analyses.

Hydrogen share of final energy 2050
%

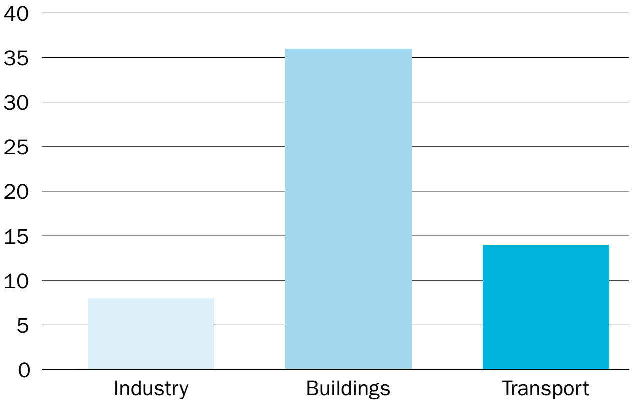


Figure 16. Hydrogen share of final energy in end use sectors in Europe in a 1.5-degree pathway in 2050. Statkraft analyses.

The massive drop in solar PV and wind power costs makes emission-free energy widely available throughout the world. Utilising this energy to cut emissions in transport, industry and buildings is generally a highly cost-effective climate measure. In Statkraft's analyses, electricity demand in the EU increases by 11% in a 1.5-degree pathway compared to the Low Emissions Scenario over the period. New solar PV and wind power generation fully covers the increase in electricity consumption in 2050. New solar PV and wind power will also replace more than 80% of coal and gas power phased out of the power mix [35]. This means that 85% of power demand will be covered by variable renewable power generation in Europe in 2050 and the total renewable share will be 96% (Figure 15).

Hydrogen plays a key role in solving the climate challenge

In some areas, it is difficult to electrify energy demand directly. If a 1.5-degree pathway is to be reached, emissions-free hydrogen becomes a cost-effective solution in several applications. Its properties – zero emissions, flexible storage potential and applicability across sectors – make the different forms of hydrogen a cost-effective low-emissions solution. The proportion of hydrogen in Europe in our analysis therefore rises by almost 150% in a 1.5-degree scenario compared to the Low Emissions Scenario.

Cost reductions for renewable hydrogen may come quickly, driven by lower technology costs for renewable electricity and expected cost reductions for electrolysers as production is scaled up. In our analyses, hydrogen from renewable electricity using abundant solar and wind resources soon becomes competitive with fossil solutions such as diesel in heavy transport; this is also the case compared to blue hydrogen based on natural gas and carbon capture and storage (Figure 17).

Hydrogen takes up a lot of space per energy unit and must therefore be converted to liquid form or ammonia if larger volumes are to be stored or transported over longer distances (see hydrogen information box on page 17). For each conversion step, some energy is lost, driving costs up. In general, therefore, our analyses indicate that local hydrogen production from renewable electricity close to the point-of-use is usually the cheapest solution, although this will not always be possible or available.

[32] The two-degree emissions pathway means that the world has a 66% chance of keeping global warming in 2100 below 2ºC relative to pre-industrial times. Analyses range from emissions cuts in 2050 of 76% to 84% compared to 1990 for the EU, including LULUCF. The 1.5-degree emissions pathway means that the world has a 50% chance of keeping global warming in 2100 below 1.5ºC relative to pre-industrial times. EC (2018): https://ec.europa.eu/clima/policies/strategies/2050_en

[33] NEEA metastudie (2018): http://www.pbl.nl/en/publications/global-and-regional-greenhouse-gas-emissions-neutrality, JRC Global Energy and Climate Outlook 2018: https://ec.europa.eu/jrc/en/geco

[34] Statkraft's energy system model mainly analyses cost-effective combinations of technology solutions across sectors and to a lesser extent lifestyle changes. EU 2050 strategy: https://ec.europa.eu/clima/policies/strategies/2050_en, scenarios 1.5TECH. 1.5LIFE

[35] The remaining 20% will be replaced by bioenergy, hydropower and nuclear power including some hydrogen and bioenergy with carbon capture and storage.

Electrification and energy efficiency are the most important climate solutions when moving from a two-degree to a 1.5-degree pathway. Photo: Getty Images/Werner Nystrand/Folio

Capital cost range for 100 MW electrolysers
EUR/MW (in thousand)

Total costs of hydrogen production
EUR/MWh

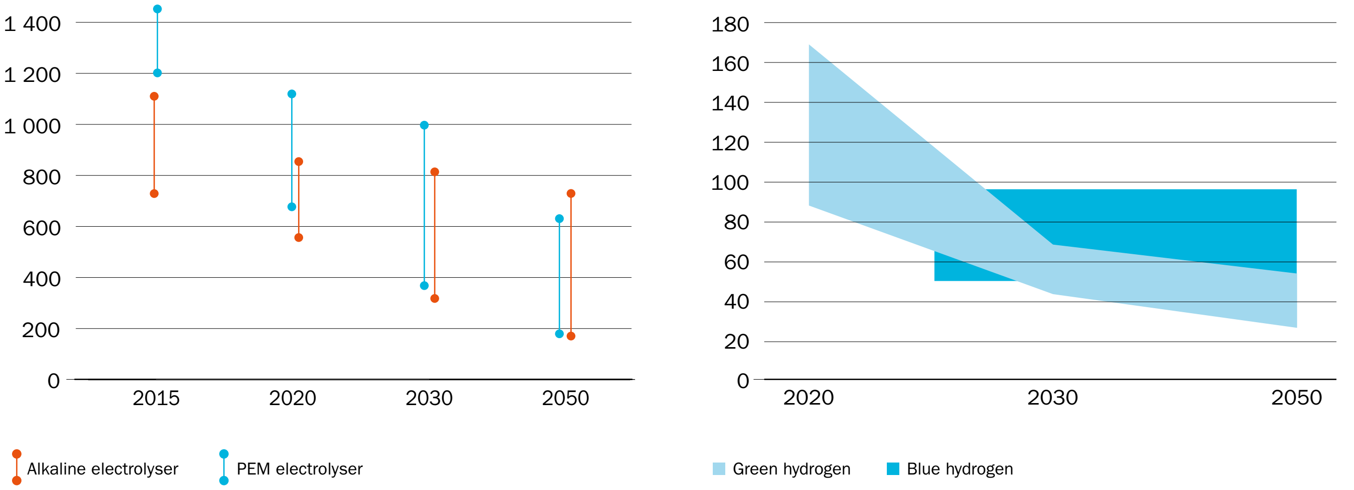


Figure 17. Illustration of cost developments for electrolysers, external sources (left). Total cost of producing green and blue hydrogen (right). Statkraft analyses and IHS Cera 2018. [36]

Typically, when electricity is converted to hydrogen via electrolysis, around 65% of the original energy is retained with today's technology. With improvements in electrolysis technology, this can increase up to 80% towards 2050. If hydrogen is then used in fuel cells in a truck for example, the cumulative energy losses are over 50%. Fuel cells that combine heat and power are able to retain around 60% of the original energy and will be preferable where possible. Our analyses indicate that emission-free hydrogen and ammonia will be primarily used in transport, buildings and industry. We also see a small share of hydrogen used for power generation, especially in areas with poorly developed electricity grids and some use as a replacement for natural gas after 2040.

The transport sector – Trucks, ships and planes transition away from fossil fuels

The transport sector accounted for 22% of European greenhouse gas emissions in 2017 and one third of energy consumption. Emissions from the transport sector have increased by 20% since 1990, in contrast to emissions from other sectors in Europe, which fell during the same period. Road transport is by far the largest group and accounts for more than 60% of the energy demand from the sector, followed by the maritime sector, aviation and rail (Figure 18) [37].

Energy consumption by transport type today
%

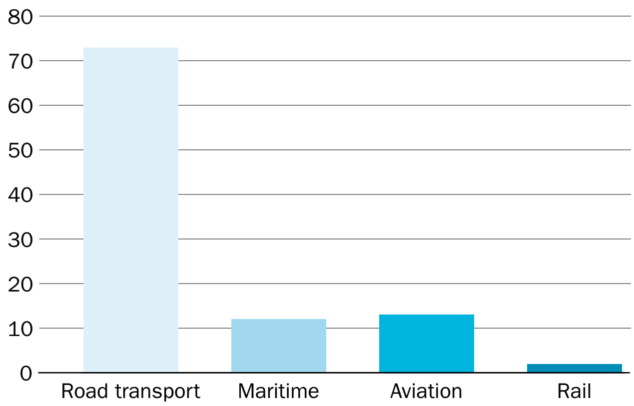


Figure 18. Energy consumption in transport today

[36] Alkaline electrolysers are currently the most common technology, while PEM (Polymer Electrolyte Membrane) electrolysers are a more expensive but more flexible technology. Costs for both are expected to fall significantly over the next ten years.

[37] European Environment Agency 2019, www.eea.europa.eu

Total costs of ownership for trucks
EUR/km

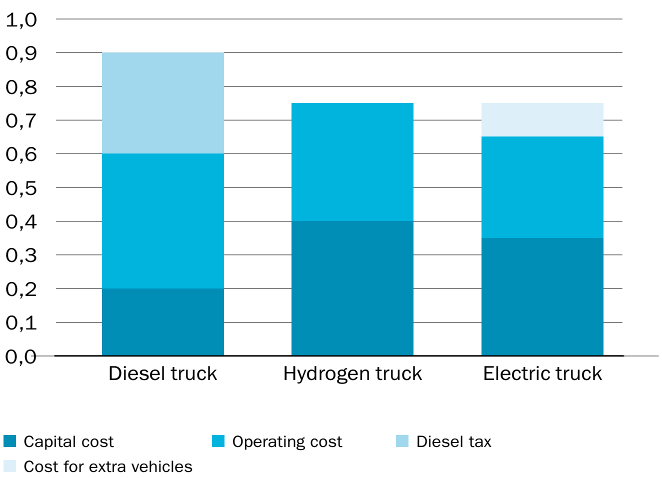


Figure 19. Lifetime cost for heavier trucks in 2030, assuming driving pattern suitable for hydrogen and electricity respectively[38]. Statkraft analyses.

In Statkraft's analyses of a 1.5-degree pathway, the transport sector is the sector with the largest greenhouse gas cuts compared to current levels. Within road transport *light-duty vehicles* account for three-quarters of greenhouse gas emissions. For this segment, electric cars will be the dominant solution, and in our analyses, they quickly become competitive with diesel and gasoline cars.

Reducing emissions in long-distance transport is more complex. In *heavy road transport* our analyses show that electric vehicles powered by either hydrogen fuel cells or batteries will dominate in 2050. Hydrogen and battery-electric trucks will complement each other for different applications depending on driving distance, load and utilisation time. Both technologies require significant infrastructure build out in charging and filling stations. As the uptake of zero emissions vehicles ramps up, emissions from fossil vehicles can be reduced through energy efficiency measures, better logistics and operational management. Natural gas, biofuels and synthetic fuels will also have a role to play in the transition towards zero emissions. We expect that some goods transport will be shifted from road to train but achieving this modal shift is challenging and we expect the majority of goods will continue to be transported by road. Heavy road transport is expected to face increasingly stringent emissions requirements[39].

An analysis of the total cost of owning a diesel truck compared to an electric or hydrogen truck shows that both electric and hydrogen-powered trucks are competitive with diesel trucks from the end of the 2020s. The energy efficiency gains from switching from an internal combustion engine to an electric drivetrain are an important factor in determining the relative competitiveness. The local diesel tax rate and the tariff structure for electricity will also impact the profitability. Other criteria, such as access to filling or charging infrastructure, availability of truck models in the market, requirements for uptime, mileage, weight and volume of load, and incentive schemes are important for each specific case (Figure 19). For example, a battery-electric truck may be more suitable as garbage truck in the city, while hydrogen may be preferable for heavy transport over longer distances with higher uptime requirements.

Solutions for non-road transport are also key for achieving a 1.5-degree pathway. There are a range of solutions available, and we foresee that all of them will be needed for different applications. Shipping and aviation are so closely interlinked globally that international cooperation to achieve climate solutions is of particular importance in these sectors.

Today, over half of all *trains* in Europe are electric, while the rest run on diesel or natural gas. Shifting a portion of transport from road or air to rail becomes an important climate solution for the 1.5-degree pathway. Towards 2050 energy use for rail transport more than doubles from its current levels in Statkraft analysis and close to 100% of the rail system in Europe will be electrified.

Shipping currently remains heavily dependent on oil. International shipping accounts for 2-3% of global greenhouse gas emissions and the sector is expected to grow due to increased global trade[40]. In shipping, various efficiency solutions will be introduced and today's heavy fuel oil will be gradually replaced with various low-emission fuels. In 2018, the International Maritime Organization (IMO) adopted a strategy to reduce GHG emissions from ships by at least 50% by 2050 from 2008 levels. This was an important milestone. Electricity in the form of batteries or compressed hydrogen will play a role for shorter and regular routes, such as domestic ferries. For longer distances these solutions have limited potential due to both volume and weight constraints. Here, synthetic fuels such as ammonia and methanol from renewable electricity are cost-effective low-emission alternatives. Natural gas, hybrid-electric vessels, improving energy efficiency and marine gas oil (MGO) are important as transitional solutions. Sustainable biofuels will have a role to play but this is expected to be a limited available resource[41].

[38] For a 40-tonne-truck, 500km of mileage per day, infrastructure costs distributed over 30 trucks. Assumes driving patterns suitable to charging and filling infrastructure.

[39] EC Clean Mobility Package (2018): http://europa.eu/rapid/press-release_IP-18-3708_en.htm. In February 2019, the EU agreed on the first emission targets for trucks (in trilogue).

[40] EC (2018): https://ec.europa.eu/clima/policies/strategies/2050_en, DNV GL (2018): https://eto.dnvgl.com/2018

[41] EC (2018): https://ec.europa.eu/clima/policies/strategies/2050_en, Energy Transition Commission (2018): http://www.energy-transitions.org/mission-possible, Transport & Environment (2018): https://www.transportenvironment.org/publications/roadmap-decarbonising-european-shipping. Lloyds (2018): https://www.lr.org/en/insights/global-marine-trends-2030/zero-emission-vessels-2030, DNV (2018): https://www.dnvgl.com/expert-story/maritime-impact/alternative-fuels.html

SYNTHETIC METHANOL

Emission-free hydrogen can be used with CO_2 to produce synthetic fuels, synthetic gases or synthetic products, such as methanol, methane and DME (dimethyl ether). Methanol is an alcohol and is handled in the same way as, for example, ethanol and gasoline. Methanol is an international commodity. Ships with modified engines and vehicles can run on up to 100% methanol, but today's regulations allow only around 3% methanol blended directly in gasoline. There are several types of fuel cells for methanol and some are in commercial use, albeit on a small scale. The climate effect of using CO_2 in the methanol production (CCU) depends, among other things, on whether the CO_2 that is used is recovered from fossil sources, from biological sources or is extracted from the air.

Given today's relatively cheap heavy fuel oil and the global profile of the industry, policy incentives will be required to bring about decarbonisation of the maritime sector. Changes in this sector are expected to be driven by international IMO regulations combined with regional regulations in coastal areas and ports.

Emissions from international *air traffic* today represent approximately 2% of global energy-related CO_2 emissions and are expected to rise. The climate solutions for this segment are relatively expensive and there are fewer alternatives. Sustainable biofuel is expected to be one of the few solutions suitable for long-distance aviation and should probably be prioritised for this sector. We also see that electric planes can be used for shorter distances and that there is a role for hybrid solutions and synthetic fuels.

For the transport sector in Europe as a whole, our analyses show that to move from the Low Emissions Scenario to a 1.5-degree pathway, the electricity share of total energy use in 2050 will increase by 7%. At the same time, the share of oil is set to fall by 14%. Hydrogen and bioenergy remain relatively stable, increasing by 2% and 4% respectively. The analyses include only intra-EU shipping and aviation (Figure 20).

Buildings – 80% of heating in Europe is currently from fossil fuels

More than 70% of energy used in buildings in Europe goes to heating. The rest is used in appliances and lighting. This includes both commercial and residential buildings. To follow a 1.5-degree pathway, we need a patchwork of different solutions such as improving energy efficiency, electrification, bioenergy, district heating and hydrogen. The solutions chosen will depend on costs, local conditions, availability of infrastructure and access to natural resources.

Fossil fuels today account for over 80% of heating; electricity accounts for 12%. There are wide variations from country to country. In Norway, around 70% of the heating demand is met by renewable electricity, while in the UK more than 60% comes from natural gas. Almost all UK households are currently connected to the gas infrastructure and rely on gas for heating and cooking. Household gas consumption results in large seasonal variations in gas demand with particularly high demand during the winter months. This is the case for the UK, Germany and France. In a 1.5-degree

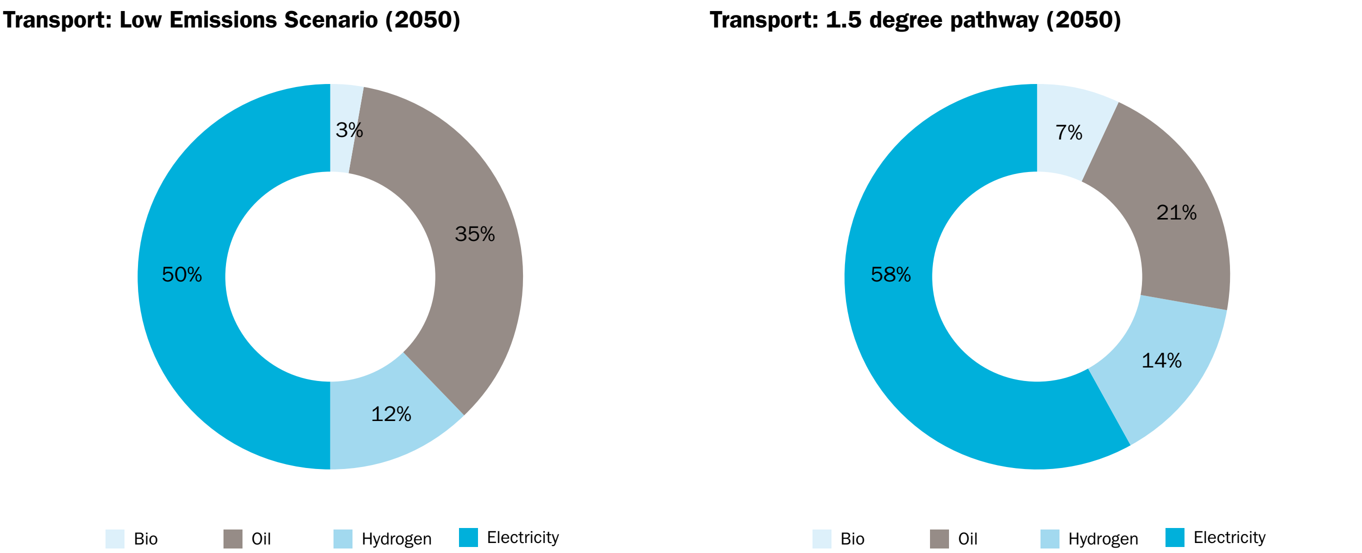


Figure 20. End-use energy in transport in 2050 by source for the Low Emissions Scenario and 1.5-degree pathway for Europe. The graphs include only intra-EU shipping and aviation. Statkraft analyses.

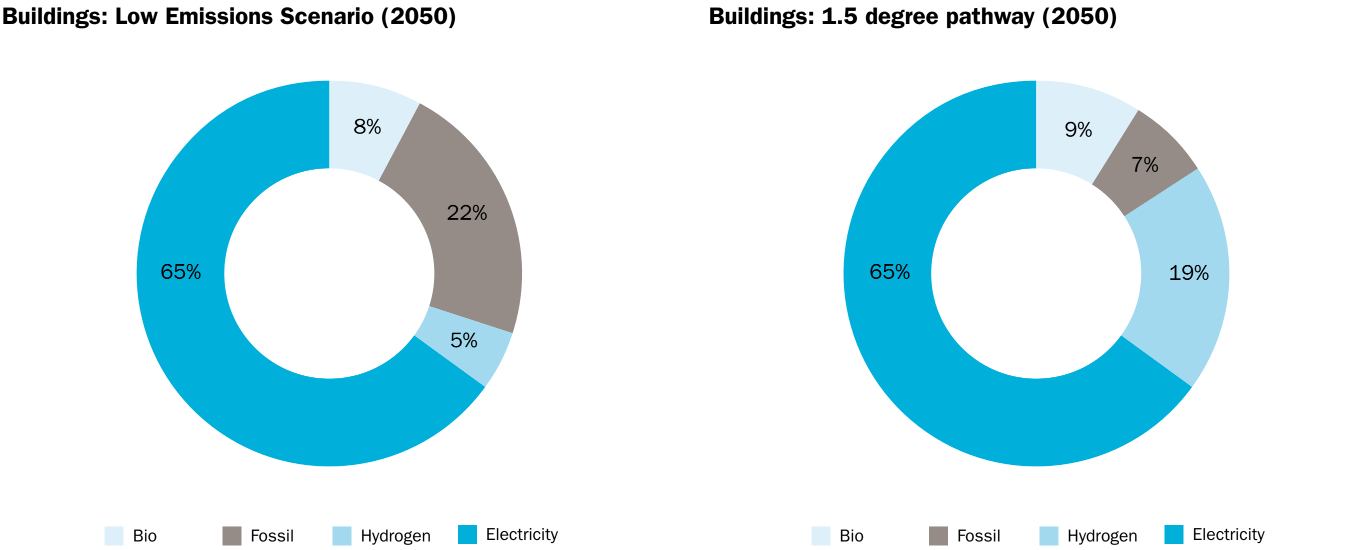
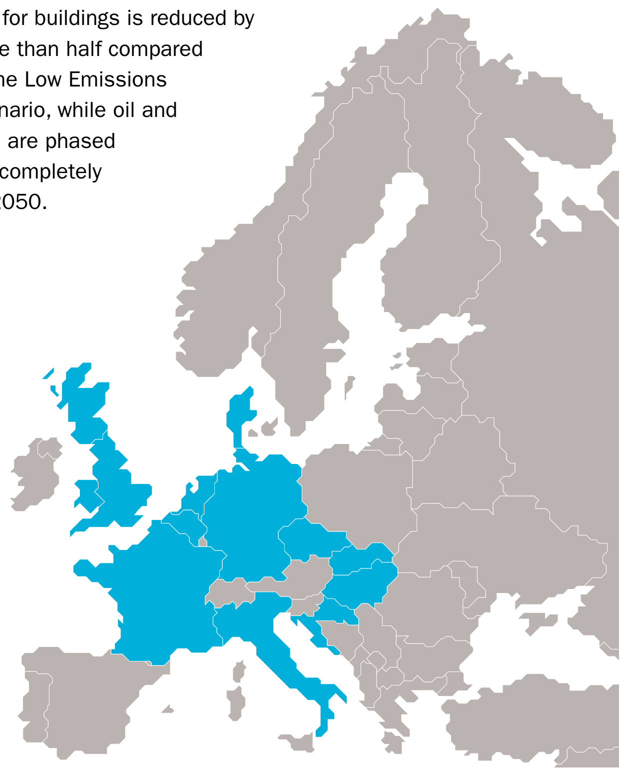


Figure 21. End-use energy in buildings in 2050 by source for the Low Emissions Scenario and 1.5-degree pathway for Europe. Statkraft analyses.

scenario, natural gas can be replaced by electric heat pumps as the most cost-effective measure, but this will not be possible everywhere. In our models, the electricity share of heating increases to 35% in 2050. Other solutions are energy efficiency measures (including building renovation), bio energy or blending hydrogen into existing natural gas infrastructure. Today, there are regulatory limits of between 5 and 15% hydrogen for blending into natural gas grids. Research is now underway on converting natural gas infrastructure and household appliances in entire cities to use 100% hydrogen in the future, including a pilot programme in the Leeds area of Northern England [42]. Converting Europe's gas infrastructure to hydrogen is a complex and long-term undertaking involving, among other things, the upgrading and replacement of pipes, compressors, burners and appliances. It would involve millions of households and therefore require government-controlled programmes.

Statkraft's analyses show that to move from the Low Emissions Scenario to a 1.5-degree pathway in Europe, hydrogen's share of total energy use in buildings will increase by 14% in 2050, while electricity will remain at around two-thirds when including appliances and lighting. Hydrogen will mainly enter the picture after 2040. The hydrogen share will be a mixture of green hydrogen from renewable power and blue hydrogen from natural gas with carbon capture and storage. Hydrogen is expected to primarily be used in the UK, France, Germany and Italy. These are countries that currently largely rely heavily on natural gas for heating. At the same time, the use of natural gas for buildings is reduced by more than half compared to the Low Emissions Scenario, while oil and coal are phased out completely by 2050.



Countries in blue account for over 85% of gas demand for heating in Europe.

[42] H21(2019): https://www.h21.green/about. Hydrogen has been blended about 50% with natural gas, both in the UK in the nineteenth century and in Singapore today.

Industry – Decarbonisation through energy efficiency and increased use of clean technologies to phase out fossil fuels

The industry sector uses natural gas, electricity, coal and oil and accounts for 25% of EU energy consumption today. In particular, it will be important to decarbonise the energy-intensive industries such as steel, cement and ammonia. The industry sector consists of many different sub-sectors with distinctive challenges and solutions. The flow of materials and products across the various sectors creates a dense network, which increases the complexity. Greenhouse gas emissions come from roughly three main sources. Two-thirds come from high-temperature process heat (either in the form of steam and hot water or from various types of furnaces). Process-related emissions from chemical reactions cover about one-fifth of the emissions, while the remainder comes from space heating. Process emissions are not further included in our energy system model analyses.

Energy efficiency and a circular economy are important ways of reducing greenhouse gas emissions in industry [43]. In addition, there are generally four different technologies that can reduce emissions in industry:

1. Use of emission-free hydrogen for heat, as a reducing agent and as an input factor
2. Direct electrification of industrial processes
3. Use of biomass for heat, as a reducing agent and as a feedstock
4. Carbon capture with utilisation or storage (CCUS)

EU 28 Industry emissions by sector today (%)

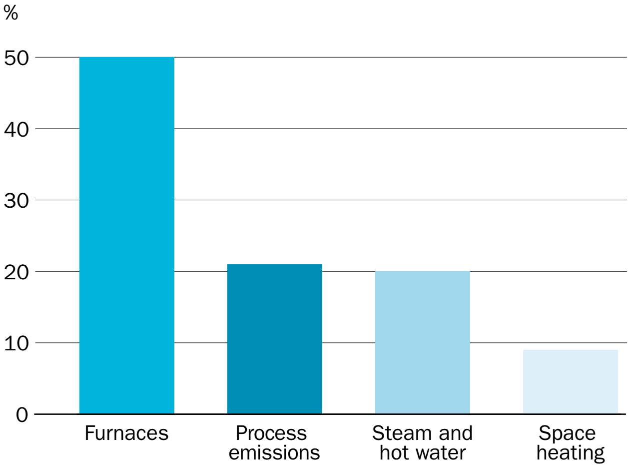
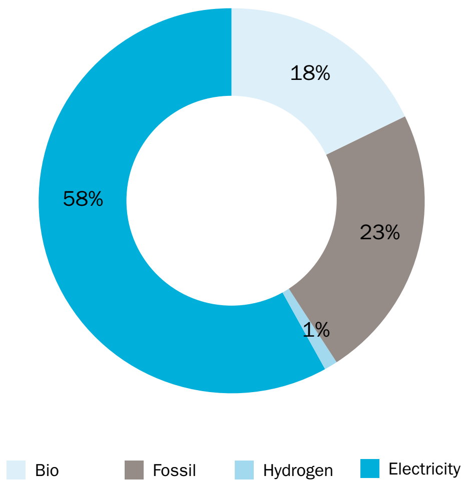


Figure 22. European industry emissions by sources excluding refineries and indirect emissions (in 2015) [44]. [1] Emissions from chemical reactions excluding combustion.

The most cost-effective alternatives vary between the different industrial sub-sectors, but also depend on, for example, physical location and access to natural resources.

Statkraft's analyses of cost-optimal solutions for Europe result in a distribution of energy consumption in industry as shown in Figure 23.

Industry: Low Emissions Scenario (2050)



Industry: 1.5 degree pathway (2050)

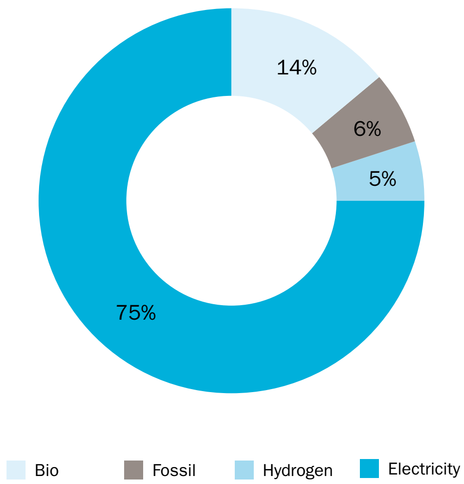


Figure 23. End-use energy in industry in 2050 for Europe by source for Low Emissions Scenario and 1.5-degree pathway. Statkraft analysis.

[43] Energy Transition Commission (2018): http://www.energy-transitions.org/mission-possible

[44] SET_NAV Project (2018), low-carbon transition of EU industry by 2050: http://www.set-nav.eu

Moving from the Low Emissions Scenario to a 1.5-degree pathway increases the electricity share in industry by around 15% while the fossil fuel share is reduced by 17%. Hydrogen's share increases by 4% while some bioenergy is shifted from the industry sector to the transport sector. This is due to sustainable bioenergy being a limited resource.

RENEWABLE AMMONIA FOR LOW-EMISSION FERTILISER AND ZERO-EMISSION FUEL

Renewable (green) ammonia based on hydrogen from electrolysis has received renewed interest in recent years. Renewable ammonia is created by adding nitrogen to renewable hydrogen in a Haber-Bosch process and converting these elements to ammonia (NH3). Ammonia is toxic and therefore requires sound safety practices that are already fully developed for industrial use.

Within industry, a gradual shift in customer preferences for green products is expected, including agricultural products based on green fertilisers. Several companies are now adapting to such a future. Therefore, an increasing volume of renewable ammonia for fertiliser production is expected in Europe and globally.

Green ammonia is also one of the few emission-free solutions for maritime use. Ammonia is an international commodity and relatively easy to handle. It can be used as a blending product in various fuels. Over time it can also be used directly in internal combustion engines and in various types of fuel cells and is therefore an interesting candidate for zero-emission fuel. Combustion of ammonia produces NOx emissions which must be handled with a catalytic converter similar to the technology in current diesel engines. Research on using ammonia directly in fuel cells without first separating it into hydrogen and nitrogen is ongoing. In fuel cells, no NOx is created, and energy utilisation is better than in internal combustion engines. One application for ammonia in fuels cells is large ships that carry freight over longer distances. The shipping costs are lower than ships using liquid hydrogen and in addition, ammonia has better volumetric energy density than hydrogen. Ammonia is also easier to store and distribute.

The cost of green ammonia is expected to fall as costs fall for renewable power and equipment such as electrolysers and Haber-Bosch plants. Today, grey ammonia, produced from fossil fuels, is cheaper than green, but the cost difference can be gradually offset by the lower energy costs and rising CO_2 costs. Further research and development are needed, but regulatory frameworks that incentivise a transition from fossil to renewable ammonia are also required. Over time, green ammonia used as a fuel will potentially be competitive with diesel without tax.

Implications for the power sector

A transition towards a 1.5-degree pathway has major implications for the power sector. Major shifts will arise in power production, power demand and in power system flexibility.

In a 1.5-degree pathway, coal is completely phased out of the European power mix by 2040 and natural gas becomes the largest source of emissions. Gas generation in combination with flexible hydropower will be able to provide flexibility early on, including during longer periods of low wind. However, gas plant running hours are expected to fall significantly and we expect that small gas engines will replace larger gas power plants (CCGT). To balance solar-dominated systems, typically within a 24-hour period, there will be many competing *short-term flexibility solutions* such as batteries, smart charging of electric cars (see information box on page 33), flexible production, cables and grids, as well as flexible demand. With falling technology costs, the combination of solar power and batteries becomes more commercially attractive in areas with a high share of solar power (Figure 9).

The need for *emission-free long-term flexibility* over several days can be covered by hydropower, interconnectors, some nuclear power, some bioenergy and hydrogen, as well as increased demand flexibility. Cables and grids are often under-communicated as a source of flexibility and we see that the use of cross-country interconnections rises by almost 30% as we move from the Low Emissions Scenario to a 1.5-degree pathway in Europe.

The closer integration of the different energy sectors has implications for the power system in the form of increased flexibility opportunities and energy storage. With new demand added, we expect the industry, buildings and transport sectors to be far more flexible in their electricity use than what is the case today. Growing participation of the demand side in power markets will increasingly impact electricity price formation.

Towards 2050, negative emissions in the form of bioenergy with carbon capture and storage become more important (see pages 20 and 21 from CICERO). In our energy system model, nuclear power in Europe increases somewhat when we model a 1.5-degree pathway relative to the Low Emissions Scenario. Flexible, renewable hydropower will remain relatively unchanged, covering around 10% of power generation in Europe in 2050. Hydropower with reservoir has a unique ability to handle the large variations in other renewable energy sources such as wind and solar power and will therefore become an important solution for both short-term and long-term flexibility[45].

A strong CO_2 price is an important regulatory instrument for driving the power sector transition. A CO_2 price strengthens the profitability of *all* emissions-free power generation and reduces that of fossil power. With a virtually emissions-free power sector in a 1.5-degree world towards 2050, CO_2 pricing will primarily play a role in the other sectors while acting as insurance against fossil energy coming back to the power market. When we run the energy system model for Europe, we get an implicit average CO_2 cost in

[45] More details about flexibility solutions in Statkraft's Low Emissions Report 2018: https://www.statkraft.com/globalassets/explained/statkrafts-low-emissions-scenario-report-2018.pdf

2050 of 50-60EUR/tCO_2 in the Low Emissions Scenario and 120-180EUR/tCO_2 in a 1.5-degree pathway across all sectors. This reflects the costs of reducing one ton of CO_2 for society as a whole and is significantly higher than today's CO_2 price in the European Emissions Trading Scheme [46].

Increased use of electricity and green hydrogen increases power demand in Europe by 600 TWh in a 1.5-degree world compared to the Low Emissions Scenario. Renewable power generation will both cover this increased demand as well as displace a share of fossil generation. The last emissions in the power sector will be relatively expensive to remove. Within our analysis timeframe, we see that hydrogen converted back to power is more expensive than many other flexibility solutions for shorter and longer periods. This is mainly because of energy losses. We project that a relatively small share of hydrogen will be used in the power sector and that hydrogen-to-power costs could signal a price ceiling.

Changes in power production (2050)
TWh

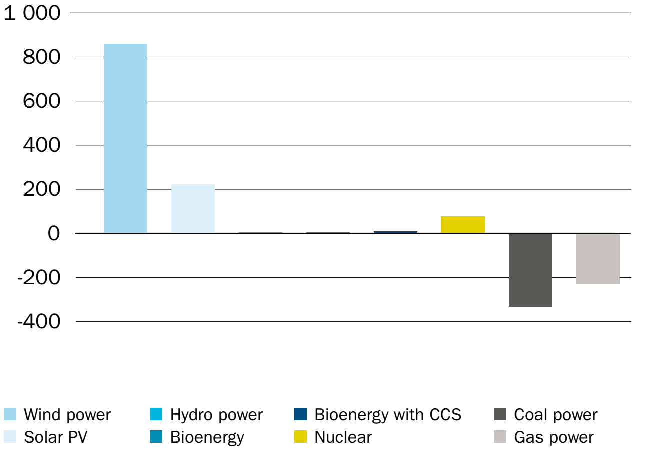


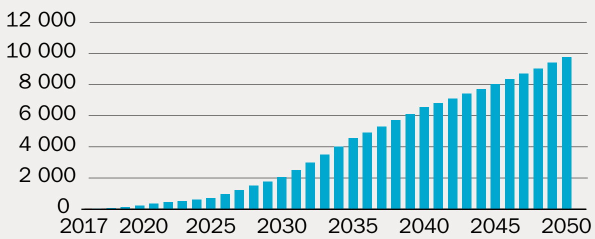
Figure 24. Changes in power generation in Europe in a 1.5-degree pathway compared to the Low Emissions Scenario in 2050 (TWh). Statkraft analysis.

THE AUTOMOTIVE INDUSTRY WILL BE IMPORTANT FOR BATTERY DEVELOPMENT. ELECTRIC CARS AND BATTERIES WILL PLAY AN IMPORTANT ROLE FOR THE POWER GRID

Lithium-ion batteries are becoming cheaper and more efficient. Technological development is primarily driven by the automotive industry. In 2030 the automotive industry expects an annual production capacity of 35 million electric cars [47]. This is in line with our analyses of demand and is a significant increase from the approximately two million electric cars sold last year. In addition to electrifying the transport sector, batteries can provide short-term balancing in the power grid – from a few seconds to a few hours. A great deal of research and development is being done on battery technology that will improve energy density, storage, lifetime, materials use and efficiency. At the same time, batteries are designed to become more customised and optimised for different applications.

Smart charging of electric cars could significantly reduce costs in the power grid in many areas and even out the need for other flexibility solutions during the course of a day (Figure 25). Smart charging technology already exists. Several electric car models offer their own apps for smart charging and some countries, such as the UK, are beginning to ban the use of "dumb" chargers.

Battery capacity
GWh/yr



Day profile of a power system during one week (example)
GWh/h

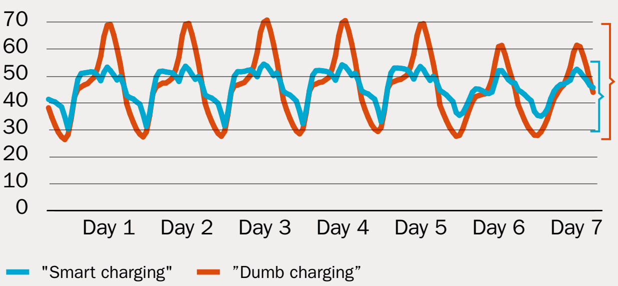


Figure 25. Battery capacity is expected to increase significantly towards 2050, driven by the automotive industry (left). Smart charging of electric cars smoothens the daily profile of the power systems – example from 2040 (right). Statkraft analysis.

[46] An implicit CO_2 cost reflects what the transition in terms of emission reductions costs society as a whole. The model does not say who pays or what regulatory instruments are used, e.g. carbon trading, a CO_2-tax, emissions standards or other instruments.

[47] Deloitte report (2019): https://www2.deloitte.com/uk/en/pages/manufacturing/articles/battery-electric-vehicles.html

Within road transport, light-duty vehicles account for three-quarters of greenhouse gas emissions. Here, electric cars will be the dominant solution. Photo: Grønn kontakt

How to prepare for a 1.5-degree pathway?

In order to reach a 1.5-degree pathway, it is important that the pace of the transition is fast enough. When it comes to the choice of policy instruments, it is neither possible, necessary nor advisable to decide on a precise combination of solutions today to reach an emissions pathway towards 1.5 degrees, because the combination of different solutions and paths will depend on a range of factors, some of which are not yet known. Policy instruments and regulatory frameworks should therefore, as far as possible, create strong, long-term and predictable incentives to cut emissions. In this way, market participants can choose the most cost-effective solutions within the various sectors of the economy. Ambitious climate targets, together with a strong CO_2 price, will be key elements to promote cost-effective climate solutions.

At the same time, in order to reach a decarbonised society, we already see that the following elements will play an important role:

- A renewable power sector and increased electrification require the build out of *infrastructure*. Infrastructure development needs long-term planning. This is the case for the transport sector, with charging and filling stations, as well as within the power systems. Increased electrification requires smart power grids with sufficient capacity at local level (distribution grid) and central level (transmission grids, interconnectors). Integrated power markets across geographies can benefit from the regional differences and can increase access to flexible solutions. Physical infrastructure and close cooperation between countries will make the joint transition to a zero-emission power sector more cost-efficient than if we were to rely only on national power markets.

- *Electrification* is set to increase significantly in transport, buildings and industry in Europe. It will be crucial to encourage the development of, among other things, zero-emission vehicles and ships, charging facilities in ports, heat pumps and other technologies that promote electrification. Here, both speed and volume are crucial to meeting climate targets. Norway is well positioned with a fully renewable power system, a well-developed power grid, an integrated Nordic electricity market, the highest share of new electric cars sold in the world and a high share of electricity in buildings. Europe is about to embark on the electrification path. In all the scenarios of the EU's 2050 strategy, electrification is a key part of the solution.

- The energy systems and markets must provide sufficient flexibility to absorb the high share of variable renewable power. This requires *regional cooperation and market design* to promote integrated power and energy markets. Facilitating enough flexibility and rapid decarbonisation will benefit from a level playing field between market players. Examples would be regulatory framework that does not discriminate electricity relative to natural gas nor between different types of renewable energy. Discrimination between different types of flexibility solutions should be avoided as we will need many of them: demand flexibility, batteries, infrastructure and flexible power production. It is also important that power price variations are visible to the end user. When prices in the underlying power market become more visible, this will act as a strong signal to change behaviour. Consumers will then have an incentive to adjust their consumption and production in line with the actual needs of the power system. One purpose of power markets is to signal to investors when and where investment is required. One should therefore seek to avoid regulations that disturb the market signal resulting in necessary investments not being made or encouraging the wrong investments.

- We see that *renewable and emission-free hydrogen* will play an important role in multiple applications, especially in industry and transport. It is important in the next five to ten years to facilitate cost-effective production of emission-free hydrogen in order to reduce unit costs, for example for electrolysers and fuel cells. This includes technological development.

- With a 1.5-degree pathway *carbon capture and storage and utilisation* will have an important role in some industry segments, and in providing negative emissions with bioenergy. In addition, developing regulatory frameworks that facilitate *improved energy efficiency* and a *circular economy* are important.

- One of the most important measures to achieve rapid decarbonisation is a well-functioning *carbon price*. Pricing CO_2 emissions will incentivise emission-free solutions as these become cheaper relative to fossil solutions. Unlike most support systems, CO_2 pricing is technology-neutral and favours both existing and new climate solutions. CO_2 pricing thereby draws an effective distinction between polluting and non-polluting activities.

The types of policy instruments outlined above are more easily implemented if there is international cooperation supporting the Paris Agreement and international trade. The current uncertainty surrounding some countries' support for the Paris Agreement may reduce other countries' willingness to fulfil their obligations. Increasing protectionism is another factor that may hamper the pace of the transition. In order to realise the large volumes of renewable power, infrastructure and green solutions that are needed to reach a two-degree and a 1.5-degree pathway, it is imperative that investors want to invest and expect an adequate return. Creating sound and efficient energy markets across countries and sectors helps reduce the transition costs. The market, technology and policy all need to move in the same direction.

Much of the opposition we see to climate policy today is due to resistance to increased costs. When the world shifts from coal to renewable energy, and from diesel to electric cars, there will be winners and losers. In order to ensure broad public support and the legitimacy of climate policies, efforts must be made to ensure that the social distribution effects are as equitable as possible.
This must take place along several axes: geographically among

countries and socially between different socio-economic groups. In addition, efforts must be made to ensure that climate policies are equitable over time. A rapid transition will require major investments. Still, the consequences and risks associated with climate change mean that rapid transition will *be less costly compared to the lack of action*. This is addressed in the next section.

Failing to meet climate targets involves dramatically higher costs

Globally, the cost for society of meeting the climate targets is estimated to be much lower than the cost of failing to make the necessary changes.

When we model Europe's energy system, we are assuming a cost-effective restructuring of the energy system and close interaction between energy sectors. The model results indicate a relatively small change in costs relative to GDP, when taking into account the need for increased investment to move to a renewable energy system. System costs increase by less than 1% of GDP when the energy sector is restructured from a reference pathway to a two-degree pathway and again by **less than 1% of GDP** when moving from a two-degree pathway to a 1.5-degree pathway [48]. This is aggregated over the period from today until 2050. We see that investment costs constitute an increasingly higher proportion of system costs as we move to a more renewable energy system while operating costs fall as fossil energy is phased out. Corresponding cost analyses in the EU's 2050 climate strategy scenarios also show an average cost increase of less than 1% of GDP to restructure the energy systems from a two-degree pathway to a 1.5-degree pathway in 2050 [49].

There are major uncertainties associated with the costs of the consequences of global warming. These costs are related to extreme weather conditions, rising sea levels, and impacts on productivity and health, food production and human migration. An increasing number of researchers and analytical communities seek to quantify these costs and compare them against the costs of meeting the climate targets. One study from Stanford University (2018) calculated the cost savings of moving to a two-degree pathway compared to a reference pathway at between 5% and 10% of world GDP in 2100, while the cost savings of achieving a 1.5-degree pathway over a two-degree pathway corresponded to 3% of GDP. An analysis performed by IRENA (2019) concluded that a transition to a 1.5-degree pathway would increase global GDP by 5.3% relative to a reference scenario when the costs of climate change are taken into account (excluding rising sea levels and extreme weather) [50].

The current low solar PV and wind power costs, which continue to fall, and future reductions in the cost of other clean technologies have put the world in a position where the affordability of moving to a low-emission world are forecasted to be far lower than expected just a few years ago. In addition, these costs are expected to be far lower than the high and uncertain consequences and costs of climate change if we fail to limit global warming to below 1.5 degrees.

Solutions to the climate challenge exist, and the costs of transforming the energy systems to meet a 1.5-degree pathway are estimated to be significantly lower than the societal costs of increased global warming. The major challenge the next years is thus to mobilise for and manage the rapid transition that is needed in order to limit global warming to 1.5 degrees.

[48] Statkraft energy system model, 2018 real. Discounted capital costs including changes in inter-country connections. Changes in local energy distribution, local power grid and investments in energy efficiency are not included.

[49] EC 2050 strategy. Energy system costs include capital costs and energy prices, including investments in improving energy efficiency. Energy system costs as a percentage of GDP are set to rise towards 2030 and then fall for all scenarios relative to today by between 0.2% and 2.6% in 2050. The share of GDP is lower than previous EU estimates, mainly due to lower projected technology costs. https://ec.europa.eu/clima/policies/strategies/2050_en

[50] IRENA (2019): https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf,
Stanford (2018): https://www.nature.com/articles/s41586-018-0071-9

Photo: Getty Images/Vstock

Key figures	Statkraft's Low Emissions Scenario (2019)	IEA New Policies scenario (2018)	IEA Sustainable Dev. Scenario (2018)	IRENA REmap (2018)	IHS CERA Rivalry (2018)	DNV GL ETO (2018)
Global energy-related CO_2 emissions ($GtCO_2$) in 2050	18	36 (in 2040)	18 (in 2040)	9.7	38.6	20
Average annual growth in primary energy demand 2017–50	0.3%	1.0% (to 2040)	-0.1% (to 2040)	-0.3%	0.9%	-0.6%
Oil consumption: average annual growth 2017–50	-1.7%	0.4% (to 2040)	-1.5% (to 2040)	-	0.4%	-2.0%
Natural gas consumption: average annual growth 2017–50	0.4%	1.6% (to 2040)	0.4% (to 2040)	-	1.6%	0.1%
Coal consumption: average annual growth 2017–50	-3.2%	0.1% (to 2040)	-3.6% (to 2040)	-	-0.1%	-3%
Transport sector						
Oil share (final, % of Mtoe, in 2050)	44%	82% (in 2040)	60% (in 2040)	33%	79%	38%
% Electric cars of new car sales in 2050	98%	-	-	-	34%	50% in 2033, 100% in 2050[51]
Power sector (Annual growth in production, % of TWh, 2017–50)						
Demand	2.5%	2.0% (to 2040)	1.6% (to 2040)	2.2%	2.9%	2.9%
Wind power	8.5%	6.6% (to 2040)	8.9% (to 2040)	8.9%	6.0%	9.2%
Solar PV	12.5%	10% (to 2040)	12% (to 2040)	12.2%	7.9%	13.5%
Hydropower	1.6%	1.8% (to 2040)	2.3% (to 2040)	1.8%	1%	1.4%
Fossil fuel share in power sector (% of TWh, 2050)	12%	49% (in 2040)	20% (in 2040)	9%	52%	15%

Table 1. Key figures in Statkraft's Low Emissions Scenario compared with IEA, IRENA, IHS Cera and DNV GL[52]

[51] Read from graph, DNV ETO 2018.

[52] The scenarios are based on different assumptions and are therefore not directly comparable. The IEA, NPS, DNV ETO and IHS scenarios are their reference scenarios. Statkraft Low Emissions Scenario is a technologically optimistic and realistic scenario.

Statkraft AS
PO Box 200, Lilleaker
NO-0216 Oslo
Norway
Street address: Lilleakerveien 6

www.statkraft.com

For more information:
Lars Magnus Günther
lars.gunther@statkraft.com

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