Statkraft

2024

Green Transition Scenarios

Location: Mauranger hydropower plant, Vestland, Norway, Photo: Ørjan Solheim

Contents

How fast is fast enough?

Birgitte Ringstad Vartdal

When it comes to the energy transition, that is a question I consider often. The challenges before us are immense and urgent.

The last year has been the hottest our planet has ever recorded — a harsh reminder of what is at risk and the millions of lives already impacted by severe flooding, wildfires, drought and more. At the same time, it is becoming more and more obvious that neither a successful energy transition nor effective climate action can be achieved without working in tandem with nature.

Simultaneously, the energy security of countries and regions such as the EU remains a critical concern for governments and business leaders alike. Exacerbated by 2022's energy crisis, security of energy supply is among the vital foundations of European competitiveness and prosperity.

It is, in short, a challenging picture. Thankfully, though, it is not the whole picture.

A CRITICAL PERIOD FOR THE ENERGY TRANSITION

We are living through a critical period of development for clean, renewable energy in the EU and globally. As this report states, cost competitive clean technologies are growing at an unprecedented speed, defined by significant cost declines in solar PV, wind power, and batteries in recent decades.

Globally in 2023, the capacity of renewable additions increased by almost 50% (that's the 22nd year in a row that renewable capacity additions have set a new record).[i] In the first half of 2024 alone, half of the EU's electricity generation came from renewable sources.[ii]

According to the IEA, total energy investments worldwide in 2024 are expected to be more than $3 trillion, two trillion of which will flow into clean tech and renewables (in comparison, just over $1 trillion will go towards fossil fuels).[iii]

THREE SCENARIOS FOR THE ENERGY FUTURE

The potential of the energy transition is considerable, from leveraging technical innovation to mitigate the speed of climate change, while also enabling national security and economic development.

That is the context in which our analysts have modelled three scenarios for the energy transition scenarios (Green Transition, Clean Tech Rivalry, and Delayed). Across these scenarios, they project what it will take for the globe to decarbonise, and what is most likely to accelerate or delay that process.

This report does not suggest that there is a silver bullet to the decarbonisation of society. What it does is articulate which solutions will make the difference between winning the race or falling short. What role, for example, will green hydrogen play? And to what extent can industry, buildings, and transport feasibly expect to decarbonise without increased policy pushes in the right places?

All of this does not ignore the realities that an increasingly tense period of geopolitics can have on much-needed global cooperation. Tensions are escalating at a time when a sense of communal progress has rarely been so essential. As news cycles abound with stories of Russian aggression in Ukraine, a tragic escalation of violence in the Middle East, and east-west trade wars, the effects for the energy transition and energy security both in the EU and globally are stark.

A CATALYST FOR THE ENERGY TRANSITION

Given the challenges, there is little point in diluting the truth: we do not have the luxury of time to transition to clean energy sources to curb climate change or to protect countries and economies against ongoing threats to their energy security. Neither do we have the luxury of inaction. As the projection for global CO2 emissions to 2050 in this report outlines, the ambition of limiting global warming to just 1.5 degrees may have escaped our grasp. Yet we cannot afford to be demotivated. We must leverage analysis such as this as a catalyst in a race where every single decimal counts and transitioning to clean energy is the most cost-effective solution.

As an industry leader, Statkraft recognises its responsibility in this transition. In collaboration with communities, societies and partners, the actions we take today — whether by scaling up renewable energy projects, enabling the industries to decarbonise, or advocating for progressive policies — will determine the speed and success of this transformation.

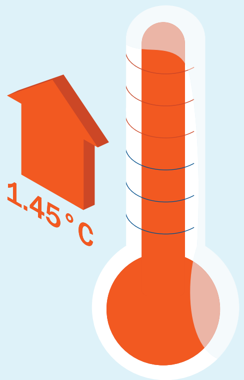
The message is clear: the path to a sustainable energy future is neither straightforward nor easy, but it is achievable with decisive action and collective effort.

[i] IEA (2024), Renewables 2023
[ii] Ember (2024), Wind and solar overtake EU fossil fuels in the first half of 2024
[iii] IEA (2024), World Energy Investments 2024

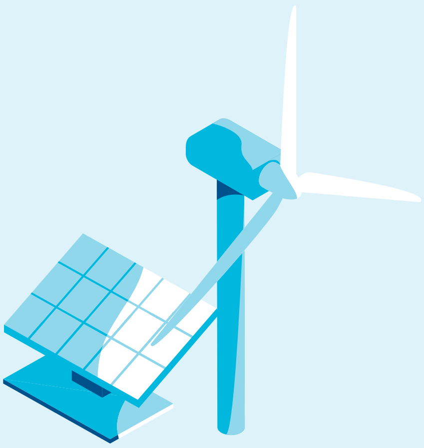
Location: Kjøllefjord wind farm, Finnmark, Norway

SUMMARY OF

Green Transition Scenarios 2024

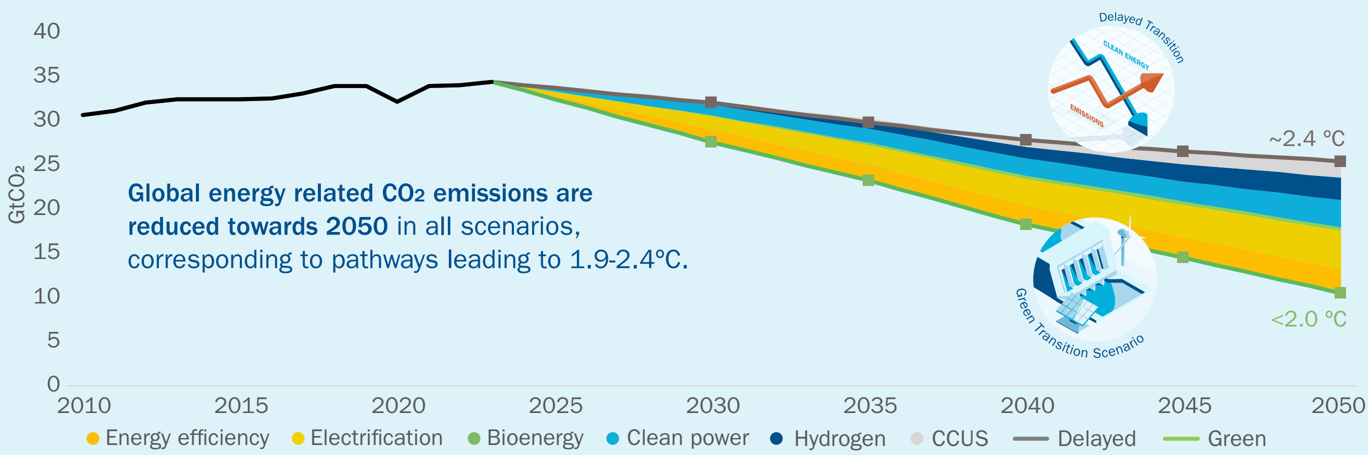


Amidst a new security situation and more fragmented political landscape, **a rapid transition of the energy sector will continue globally, pushed forward by renewable cost declines as well as climate and energy security concerns.** In all our scenarios renewables are poised to replace fossil fuels, albeit at different rates and to different extents.



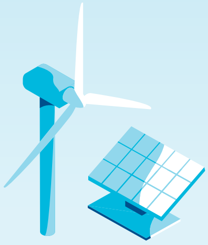
Wind and solar power are the real winners: to quadruple in the Green Transition Scenario by 2030 and increase by 13 times by 2050. Strong growth even in the Delayed Transition Scenario, increasing by six times to 2050.

Nuclear grows in all scenarios, but not to the same extent as wind and solar. Its growth is hindered by costs, long lead times, regulatory hurdles, and competitiveness of renewables.



Global energy related CO_2 emissions are reduced towards 2050 in all scenarios, corresponding to pathways leading to 1.9-2.4°C.

The European transition continues in a more geopolitical tense world, but **with a changed set of drivers.** Even in the **Delayed Transition Scenario, a massive transition will happen driven** by clean tech cost declines. But stronger policy push is needed to reach the EU climate targets in the **Green Transition Scenario.**

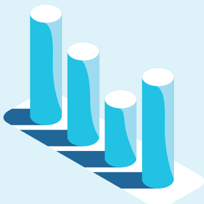


Solar generation grows eight times to 2050 while wind generation sees a growth of five times from today in the Green Transition Scenario. **The electricity sector becomes fully decarbonised by 2050**.

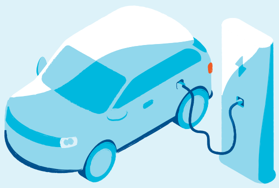
High intermittent RES share in the power system is a challenge, but it is **manageable** with **parallel build out of all types of clean flexible solutions**, including batteries, flexible hydropower, demand response, and high connectivity across markets.

Electricity's share of final energy demand in industry doubles to a share of 56% in 2050 in *Green*. In addition, **25% share is clean hydrogen.** By the help of carbon removals, industry will nearly reach net-zero by 2040.

EU electricity demand is projected to double by 2050 in the *Green* scenario mainly driven by the adoption of electric vehicles, heat pumps, and the production of green hydrogen (50% in *Delayed*).



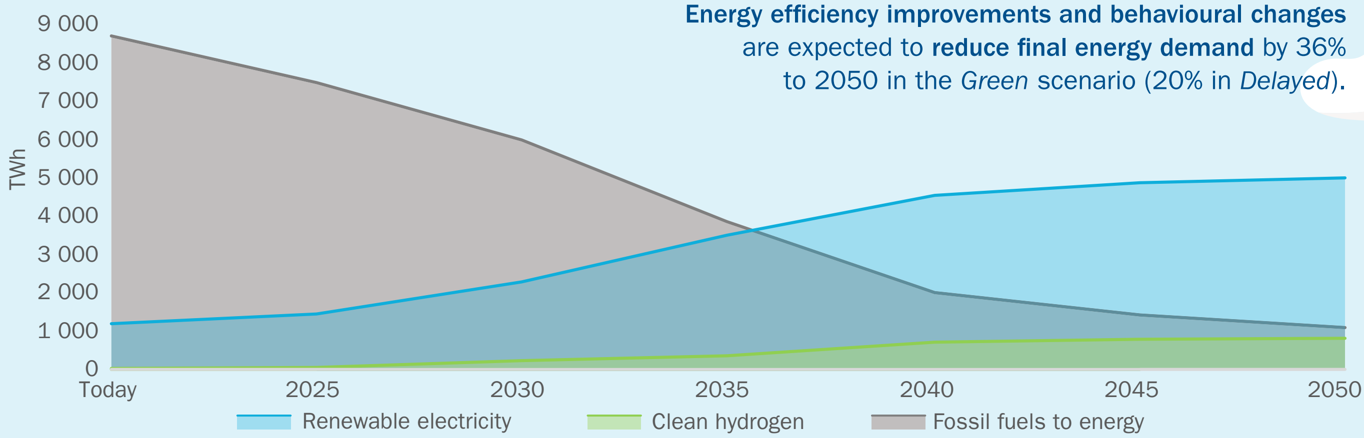
EU reaching net-zero in *Green* enabled by markets, technologies and policies mutually reinforcing each other.



By 2050, the **electricity share in transport is expected to reach almost 70% in *Green*** from 2% today.

In our scenarios, the number of **heat pumps in buildings grow five to seven times** from today to 2050.

Energy efficiency improvements and behavioural changes are expected to **reduce final energy demand** by 36% to 2050 in the *Green* scenario (20% in *Delayed*).



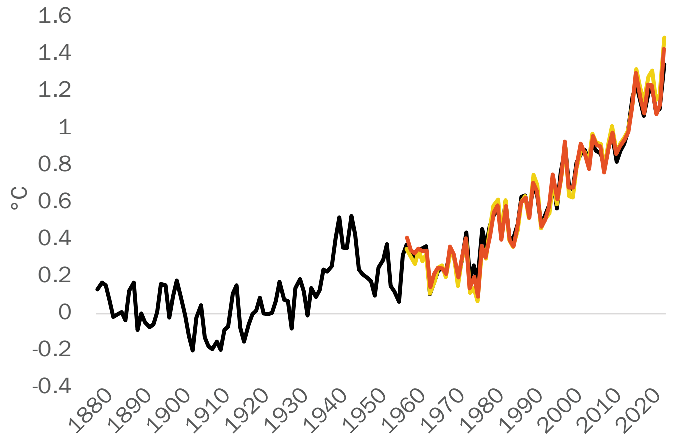
PART 1

The energy transition progresses despite challenges

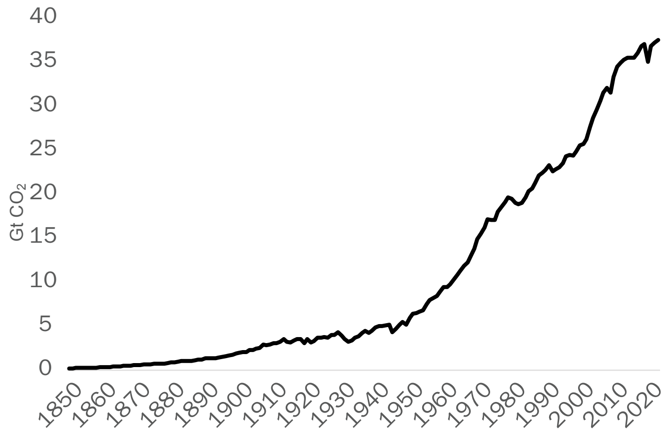
Over the past few years, policies related to energy, climate and security have become increasingly interlinked, and security policy considerations are influencing the energy markets to a greater extent than ever before. The continued strong growth in clean technologies persists, driven by both supportive policies and market conditions. Current geopolitical trends and resulting future uncertainty will impact the pace, scope, and cost of the energy transition, and thus will have consequences for the climate. In Part 1, we discuss the main challenges that the energy system and the clean energy transition currently face, and four key drivers that give reason for optimism.

Location: Roan wind farm, Trøndelag, Norway

1 Average temperature increase from pre-industrial levels.[1]



2 Global fossil CO_2 emissions from 1850-2023 (Gt CO_2).[2]



Cost of climate change is increasing while use of fossil fuels is yet to peak

Greenhouse gas emissions continue to rise, as the world faces the already severe consequences of climate change. This and last year (2023) are on track to be the hottest on record, as global temperatures breached the threshold of 1.5°C during each of the past 13 months. By the first half of 2024 there were already several cases of record-high temperatures, fires and extreme weather events around the world. A changing climate affects human life and economies in numerous ways, often with unpredictable consequences.[3]

Despite strong global climate ambitions, greenhouse gas emissions from fossil fuel combustion reached a record high in 2023, up by 1.1% from 2022. Over the past year, we witnessed the global expansion of coal and gas-fired power plants in parts of the world, and at the same time, the unprecedented growth in renewables. Emissions declined in the US and the EU last year, comprising 21% of global emissions, whereas emissions increased in India and China, resulting in 39% of global emissions. According to the IPCC, CO_2 emissions must reach net-zero by mid-century to stay within the global carbon budget as defined by the Paris Agreement. Relying on negative emissions in the future and overshooting the carbon budget represents great risk of passing climate tipping points with possible severe consequences. Rapid decline of the use of fossil fuels is therefore needed.[4]

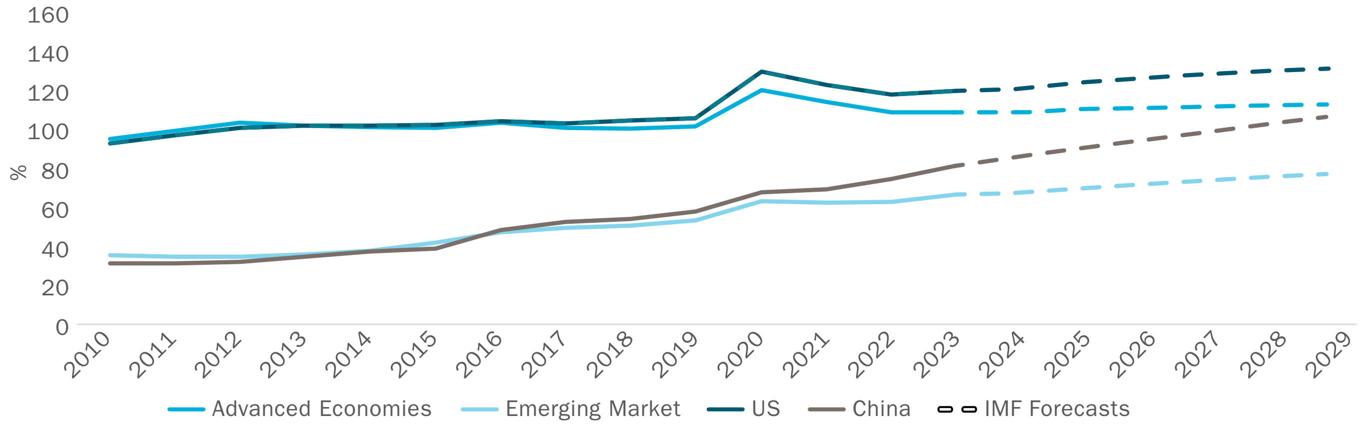
As discussed in this report, the energy transition is advancing, primarily driven by cost-competitive clean technologies, almost independent of climate policy. However, the pace of this transition and accumulated emissions depend on the speed at which policy incentives are implemented, which is crucial for stimulating technology adoption and market growth. Additionally, increasing security and competitiveness concerns in many countries and regions are further incentivising the continuation of the energy transition.

Location: Ulm, Germany

By the first half of 2024 there were already several cases of record-high temperatures, fires and extreme weather events around the world.

Location: Estreito da Calheta, Portugal

3 Development of central government debt as % of GDP.[6]



Global challenges affect the energy transition

Geopolitical dynamics impact drivers and barriers in the energy transition

We live in an era of greater geopolitical tension. The world seems to be heading toward increased confrontations and heightened tensions, fuelled by great power rivalries and competing alliances. The international political scene is fragmented and multi-polar, driven in part by stronger regional powers. The war in Ukraine, protracted armed conflicts in the Middle East and elsewhere, and increased hybrid threats from both state and non-state actors all play a role in today's situation. The rising global tensions have led to a policy and priority shift in many countries and across most sectors, including energy. Climate change and its consequences, ranging from extreme weather events to food security challenges, to climate-driven migration and resource scarcity, could further exacerbate these tensions.

China is becoming increasingly influential on the international stage, in terms of economy, military strength, and partnerships. The Chinese economy has grown an average of 5.8% annually since 2015. At the same time China is dominating the clean energy technology development and deployment. China is also building new international alliances and engaging in multilateral diplomacy, in line with the country's growing global influence and ambitions. In the long-term, US-China relations will be crucial for global conflict levels, trade, and the pace of the clean energy transition. The evolution of this relationship will shape the policy parameters for other countries, including those in Europe.

Where economic policies previously were geared towards growth, the focus has now shifted towards strategic autonomy. Trade barriers and subsidies are more frequently used to ensure national control and protection of domestic industries and creation of alternative value chains in strategic areas. For the first time in decades the growth in international trade of goods and services is slowing relative to growth in GDP, which means cross-border trade is currently a less important factor for growth than before. The West is becoming more strategic about supply chains and dependencies, as exemplified by the US Inflation Reduction Act (IRA), the EU Net-Zero Industry Act (NZIA) and EU Critical Raw Materials Act (CRMA).[5]

Political trends that will shape the way forward

As the world recovers from multiple crises – and faces new ones - most regions are expected to have a tighter fiscal balance. The global economy is currently grappling with high inflation, high interest rates, and supply chain frictions as a combined result of COVID-19, extreme and volatile energy prices, and geopolitical tension. The pace of global economic recovery remains uncertain and global public debt is higher than pre-pandemic levels (Figure 3). This is likely to lead to tougher prioritisations and increased competition over the allocation of public funds in many countries. In the longer-term, demographic changes may also shift the global power balance and constrain fiscal capacity in countries with ageing populations.

Polarisation and fragmentation have become more pronounced over the last year. The recent EU election showed an increasingly fragmented political party landscape in the union, though there are some exceptions to this trend. Political polarisation appears high in the EU, US and elsewhere, and public trust in government institutions is at a record low. More polarisation, less trust

Brazil and India, and to a certain extent the Gulf countries, are examples of markets where the transition is gaining momentum.

Location: Ventos de Santa Eugênia wind complex, Bahia, Brazil

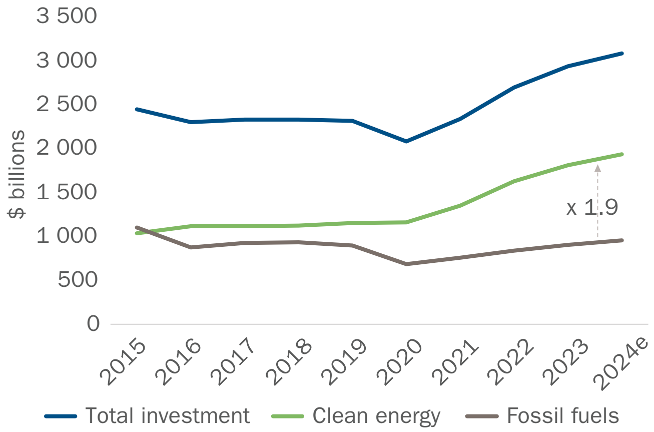
and a more fragmented political landscape may slow political processes and create greater unpredictability across markets and policy areas. As an amplifier, 2024 is a key election year for more than four billion people.

The US election result could impact the pace of the global energy transition. The emphasis on protection of American industry and jobs, and the nation's highly competitive attitude towards China, will likely persist no matter who wins the US Presidential election in November. However, the candidates hold fundamentally opposing viewpoints on key issues, including environmental policies, emissions reductions ambitions, climate and clean energy elements of the IRA, renewable energy support schemes, and commitment to international climate agreements. The election outcome could also shape the future of US-China relations, determining whether they remain competitive within internationally established norms and regulations, or increasingly hostile, confrontational, and unpredictable.

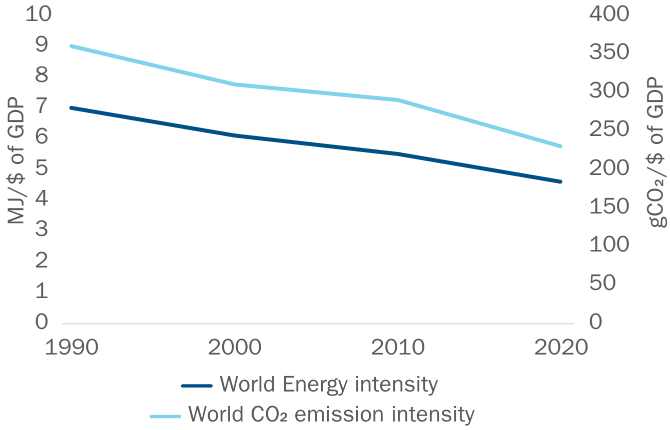
Developments in other key markets will also shape the global transition. Brazil and India, and to some extent the Gulf countries, are examples of markets where the transition is gaining momentum. Developments in these major regional powers, with regards to renewable energy systems and production of key components, will impact the pace, scope, and cost of the transition. If the trend of global fragmentation and heightened focus on alliances continues, the role of these countries will become increasingly significant in both geopolitical and economic spheres.

In summary, the geopolitical situation has an impact on the nature of the transition. Security considerations are dominant in the short-to-medium-term and could weaken the long-term focus required to reach the climate targets. On the other hand, the search for security and competitiveness promotes active policy measures that drive the energy transition forward. The speed and strength of these measures may be impacted by increased political fragmentation and an adverse economic situation. In short, the transition continues, but with a changed set of drivers.

4 World energy investments from 2015-2024.[7]



5 Global energy intensity (MJ/$) and CO_2 emission intensity (g CO_2/$) from 1990 to 2020.[12]



Global drivers which give cause for optimism

Several indicators point towards continued rapid transformation of the energy sector despite the aforementioned challenges.

Cost competitive clean technologies are growing at unprecedented speed

The global momentum for clean technologies remains strong with new records set annually. Renewable capacity experienced its fastest growth rate in 2023, increasing by 50% year-over-year with a record-breaking 510 GW of annual additions, bringing the total capacity to over 4,000 GW. More than 60% of the capacity additions for wind and solar last year were built in China. Solar PV accounted for three-quarters of the annual capacity additions making it the largest renewable technology in terms of power capacity. This surge in solar capacity was driven by record growth in China, but also by new records in Europe, the US and Brazil. Technology costs for solar PV, wind power and batteries have seen major cost declines in the last decade, increasing the competitiveness of these technologies. New wind capacity additions increased by around 60% in 2023 from the year before. Onshore wind makes up 85% of total wind capacity, with offshore wind comprising the remainder. Many countries have raised their national wind and solar capacity targets (Figure 7).[9]

In the electricity sector, global investments in clean electricity are now ten times higher than investments in fossil power. For the first time ever, more investments were made in solar PV in 2023 than investments in all other power generating technologies combined, reaching record-breaking levels of nearly 500 billion USD. Global investments in clean energy are now 1.9 times the amount invested in fossil energy. This gap has widened annually since 2019, amplified by the global pandemic and the 2022 energy crisis (Figure 4).[10]

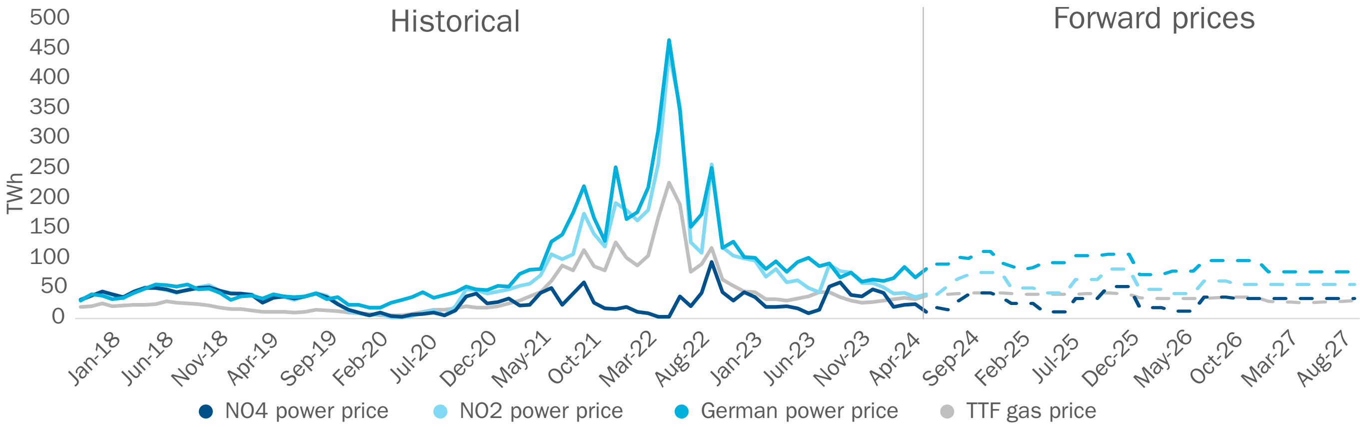
New records were achieved for global electric car sales. Sales were up 35% year-over-year in 2023, amounting to sales of almost 14 million cars. China, Europe, and the US accounted for nearly 95% of these sales. Currently, the energy and transport sectors are responsible for 90% of annual global lithium-ion battery demand. More than 90% of this demand stems from batteries used in the approximately 40 million electric vehicles currently on the road. Additionally, battery storage capacity reached new levels in 2023, with a doubling of capacity year-over-year. The development of system batteries is expected to be closely linked to the sales of electric cars. In the long term, supply of lithium is expected to be adequate as production capacity grows, and as other battery types (such as sodium-ion batteries or flow batteries) gradually gain market share, thereby reducing the pressure on supply.

Energy, mineral and metals prices are normalising

Energy prices have normalised after the global energy crisis in 2022, triggered by the war in Ukraine. Lower gas prices, more renewables, and less consumption have reduced European power prices by more than 50% in 2023 compared to 2022. In the US, power prices were 40% lower over the same period. Although average European power prices were less than half of the average 2022 prices and fossil fuel generation was 22% lower, gas and power prices in Europe remain above pre-2022 levels (Figure 6).[11]

Lower prices for key minerals and metals help drive

6 European gas price, German and Norwegian power prices historical (2018 – Aug 2024) and forward price from Aug 2024 to 2027 (EUR/MWh, nominal, monthly).

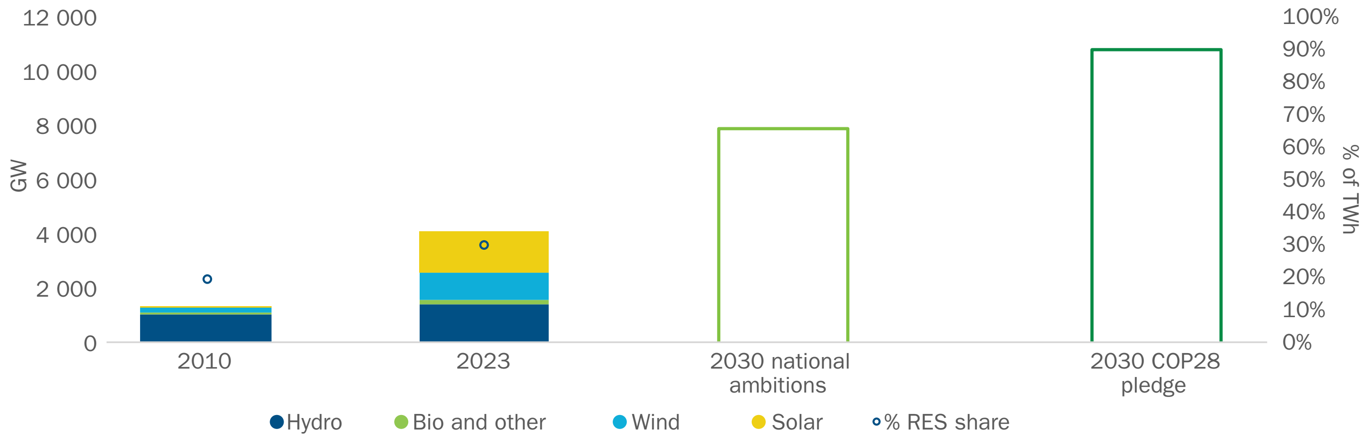


down the cost of clean technology. Supply chain resilience has emerged as a key topic particularly since COVID-19, the Ukraine war and the rise of more protectionist and security-focused trade policies. The supply chain disruptions and high commodity prices caused by the pandemic and Ukraine war have come down from the elevated levels, with some even to pre-pandemic levels. In the case of onshore wind, turbine prices from Western manufacturers have risen over the past few years driven by higher raw material and freight prices and supply chain pressures. However, there are now signs of these costs decreasing. For solar PV and batteries, costs have reached new record lows, dropping below pre-pandemic levels. In 2023, lithium prices declined significantly, and storage battery pack costs fell by 14%, also hitting record lows. This decrease was driven by falling commodity prices and increased manufacturing capacity.

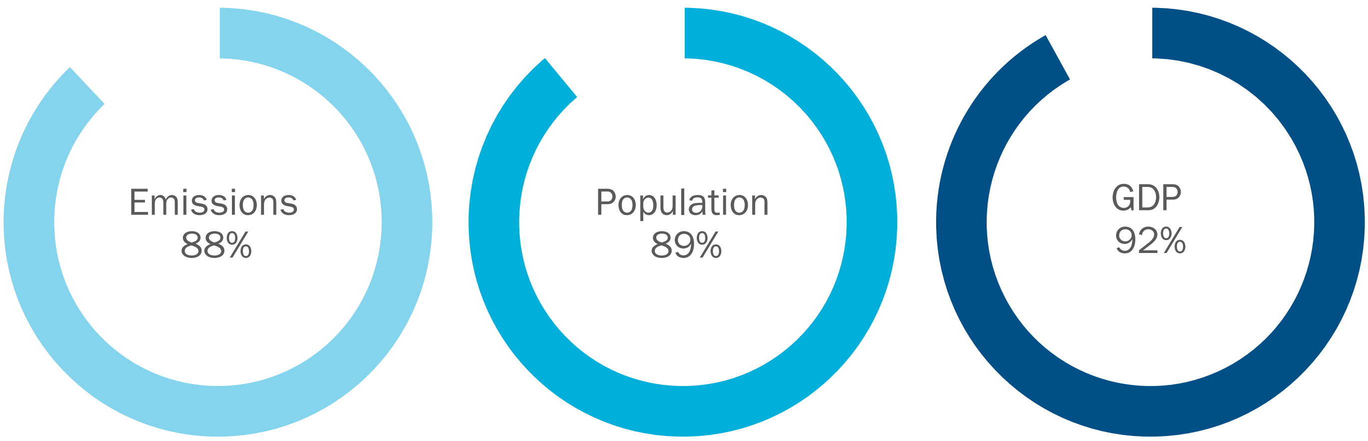
Energy supply and emissions decoupling from economic growth

The global economy has seen substantial reductions in energy and emission intensity over the past few decades. Energy intensity has fallen globally by 36% from 1990 to 2022, with an annual energy intensity decline of 1.6% from 2010 to 2020 (Figure 5). This trend spans multiple sectors due to building retrofits, industry efficiency improvements, fuel efficiency gains, and increased electrification of heat and transport. Despite a slowdown in 2020 and 2021 due to COVID-19 lockdowns, the 2022 energy crisis prompted an increase in energy security policies that in turn accelerated global energy efficiency improvements.[13] As the energy intensity of the global economy decreases, so too does its emission intensity, requiring less fossil fuel for the same level of economic output over time.

7 Cumulative renewable capacity (GW).
Historic renewable share in power generation (% of TWh).[8]



8 The world's emissions, population and GDP that are covered by net-zero ambitions.[15]



CO_2 emissions peaked in advanced economies in 2007 and have declined ever since, despite continued GDP growth. The drop in emission intensity is caused by a combination of rapid growth in clean energy investments, electrification and more renewable electricity, improvements in energy efficiency and a shift from a heavy industry to a more service driven economy. The EU's economy has grown 66% since 1990, while CO_2 emissions have dropped 33%. The US economy has doubled, while its emissions have remained roughly the same. Emerging economies such as China and India are also seeing a decoupling of CO_2 emissions and GDP growth. In China, the economy has experienced 14-fold growth since 1990, while the country's emissions have increased five-fold. India has experienced a similar situation, in which GDP growth has outpaced CO_2 emissions by over 50%. In Southeast Asia and the Middle East there remains a close connection between GDP growth and CO_2 emissions. Cheap coal is meeting Southeast Asia's rising demand in industry and power generation, while access to cheap fossil fuels, combined with substantial fossil fuel subsidies, has resulted in inefficient and emission-intense energy demand growth in the Middle East.[14]

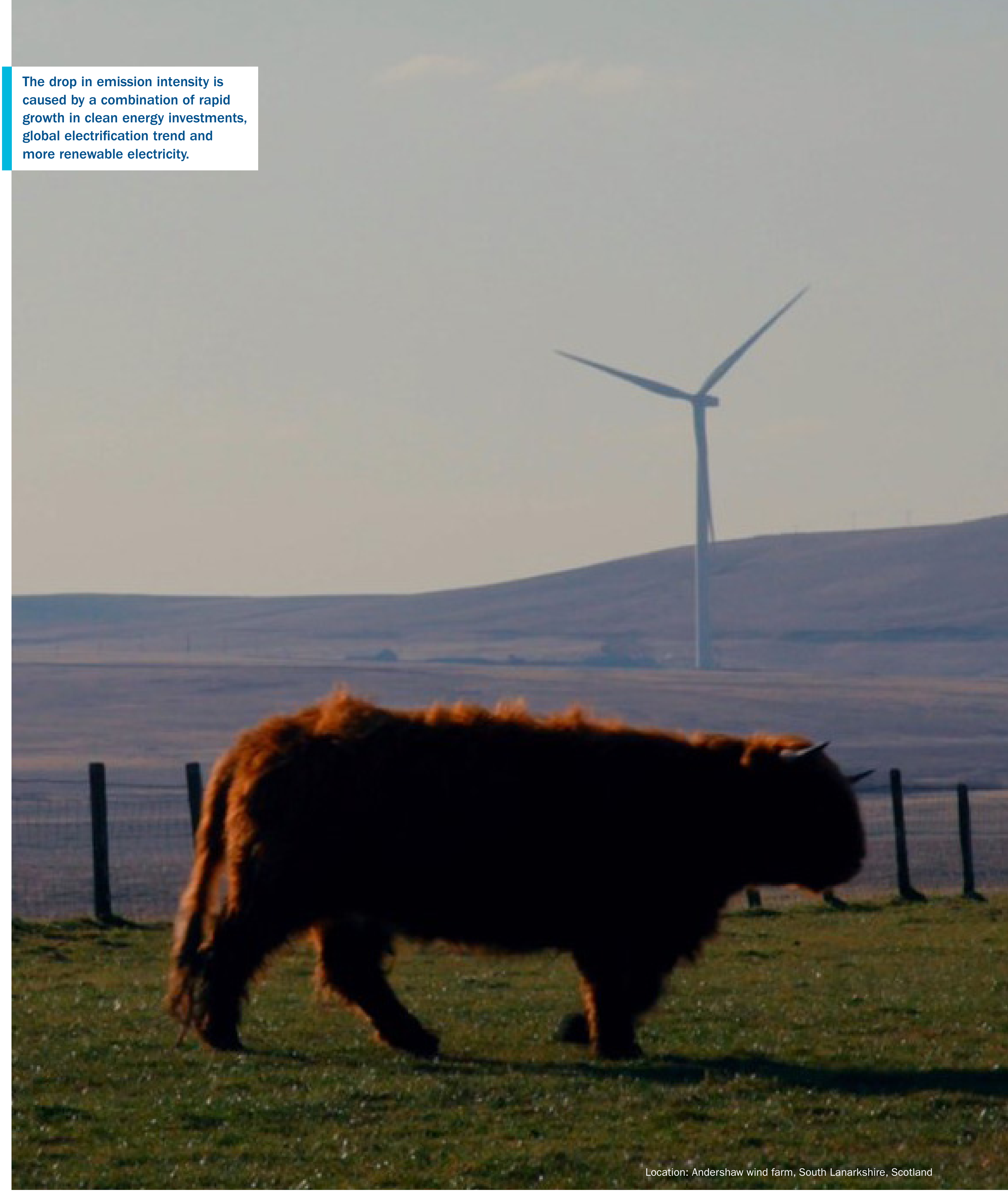
Global climate policies remain strong

Despite greater geopolitical tensions, the climate policies of the major economies remain strong and have been strengthened in some regions. Currently 88% of global emissions and 92% of global GDP are covered by net-zero ambitions (Figure 8). This includes 148 out of 198 countries. All G20 countries, except Mexico, have set net-zero targets, and the US and the EU are demonstrating that the disconnection of economic growth from fossil fuel consumption is possible. Together, the G20 countries now represent 76% of all global emissions.
These net-zero targets vary greatly in scope, coverage, timeline, and commitment. If all net-zero ambitions and current national Paris Agreement pledges (Nationally Determined Contributions) are implemented, the world will be on track for a temperature increase of 2°C.[i,16]

There is uncertainty about whether current Nationally Determined Contributions (NDCs) under the Paris Agreement will be achieved and whether ambitions will be sustained. There has been (and remains) political uncertainty regarding governments' willingness to uphold climate ambitions after elections in important regions and countries. According to the Paris Agreement, all countries are expected to deliver their post-2030 goals nine-to-12 months prior to COP 30 in November 2025. The 2024 US federal election will be crucial for global climate action and cooperation, even though a significant portion of US climate policy is driven at the state level. The uncertainty remains high for other major emitters like India and China. Meanwhile, election outcomes in Europe suggest a continued commitment to reducing emissions.

Cost competitiveness drives the continued shift away from fossil and to renewable energy. Carbon pricing is essential and steadily increasing in scope and price level globally. More weight on social justice and competitiveness, the need for fast and deeper emission cuts combined with environmental concerns means that other climate policy tools in addition to carbon pricing are important. Currently 24% of global emissions are covered by carbon pricing as tax or emissions trading. Carbon pricing revenues reached a record-high of 104 billion USD last year. The largest scheme is the Chinese national Emission Trading Scheme (ETS) which started in 2021. It covers 31% of domestic emissions, with ambitions for expansion. This is followed by the European EU ETS, in operation since 2005 and covering 38% of EU emissions.

The drop in emission intensity is caused by a combination of rapid growth in clean energy investments, global electrification trend and more renewable electricity.



Location: Andershaw wind farm, South Lanarkshire, Scotland

In the EU, the Carbon Border Adjustment Mechanism (CBAM) was adopted in 2023. If successful, this will be an important policy instrument for reducing the risk of carbon leakage while simultaneously putting pressure on EU trading partners to implement carbon pricing to reduce the levy to the EU. Due in part to CBAM, positive progress on carbon pricing was observed in several countries last year, including Brazil, India, Turkey, Colombia and Chile. In parallel, direct regulations and support are implemented in many countries and regions to speed up and facilitate the transition. More weight on industrial competitiveness and negative consequences for vulnerable groups have led the EU and others to implement policies for a more just transition, such as the Social Climate Fund.[17]

[i] (Range: 1.8–2.5°C) with 66% chance over 2100.

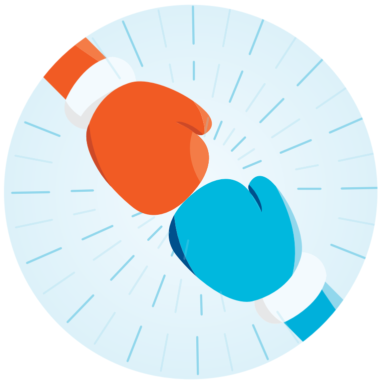
PART 2

Global scenarios: The energy systems are rapidly changing

The recent crises and the large fluctuations in energy prices, demand, and supply that we have observed in recent years, run the risk of potentially concealing long-term trends. Therefore, it is important to assess both short-term variations and long-term patterns in our analysis to gain a better understanding of likely future outcomes. Our scenarios detail three different outlooks for the global energy future towards 2050.

Location: Oostrumsdijkje solar farm, Utrecht, The Netherlands

Green Transition



Clean Tech Rivalry

Delayed Transition

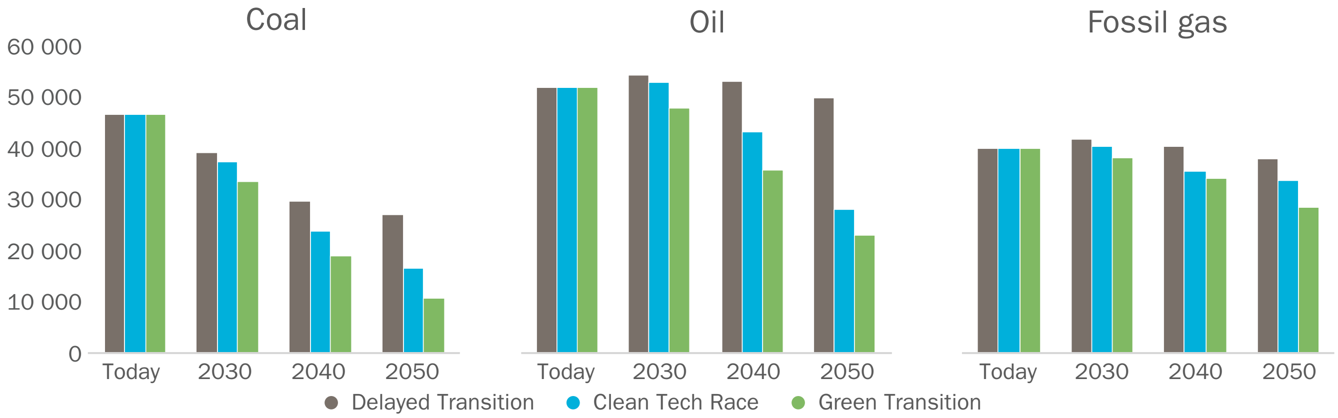
Introduction to scenarios of possible energy futures

The Green Transition Scenario is an optimistic, yet realistic scenario in which technology, market dynamics, and proactive policies accelerate the energy transition. This, combined with global collaboration, helps enable an efficient transition to cleaner energy sources, supported by globally expanding carbon pricing. In this scenario, global trade remains high despite some global tension, efficient supply chains enable robust global economic growth, and market-driven technological advancements help drive the clean energy transition. China-EU/US relations are defined by agreed-upon rules and there is improved geopolitical stability in the coming years. A stable world economy creates an enabling environment for rapid progress. The need for energy security is successfully coupled with emissions reduction policies, so that security of supply is provided by growth in renewables. Competitiveness and industrial growth are fuelled by clean technologies. This scenario foresees the energy transition accelerating in developed and developing nations, driven in parallel by international pressure and the declining cost of clean energy technologies.

In the Clean Tech Rivalry Scenario, the world's superpowers engage in a race for global dominance in clean energy and to reach climate targets. Clean energy is seen as crucial for both energy security and reducing emissions. China, the US, and the EU become embroiled in a subsidy-fuelled competition to develop clean industries and establish regional control over renewable technology supply chains. Continued high geopolitical tension leads to greater emphasis on protecting local supply chains and more trade barriers. This reduces global trade in clean technologies, resulting in a more expensive and challenging energy transition. Near-term emissions reduction targets face delays due to increased costs and the complexities of restructuring economies, industries, and supply chains. Fossil fuel prices are also impacted upwards by the heightened geopolitical tensions. Intense competition and a focus on energy security lead to a subsidy-driven scenario, and a more unpredictable transition. State-led 'picking winners' policies could result in inefficient and costlier technology choices. This spending-based approach places significant strain on public finances. High geopolitical tensions make nuclear power important for energy security and strategic for national defence. Meanwhile, the higher costs of renewable technologies, combined with limited investment and access to capital in developing countries, widens the gap between developed and developing countries.

In the Delayed Transition Scenario, increased geopolitical tensions and concerns about energy security and supply chain disruptions overshadow environmental priorities. Escalating inflation and soaring costs of living divert resources away from clean energy investments. Investments in renewable energy continue to flow in, driven by their cost-competitiveness. The lack of a policy push makes it more challenging to reduce emissions in the end-use sector – in particular, the 'hard-to-abate' sectors – and to remove costly residual emissions in the power sector. Energy security necessitates that fossil fuel technologies serve as a short-term solution. More social unrest and political instability create uncertainty and slow global economic growth. Protectionist policies become coping mechanisms for countries facing reduced standards of living. Emerging markets, hit by global economic downturn, struggle to keep pace with energy transition efforts.

9 Global fossil primary energy supply from 2010 to 2050 for the three Statkraft scenarios (TWh).



The transformation of the global energy systems towards 2050

Despite global tensions and political unrest the energy transition continues, on the back of the competitiveness of wind power, solar power and batteries across all our scenarios. However, the pace of transition in the 'hard-to-abate' sectors depends heavily on how quickly policies are implemented to accelerate technology adoption and market growth.

Renewables increase rapidly, and fossil fuels decline, but not at the same rate

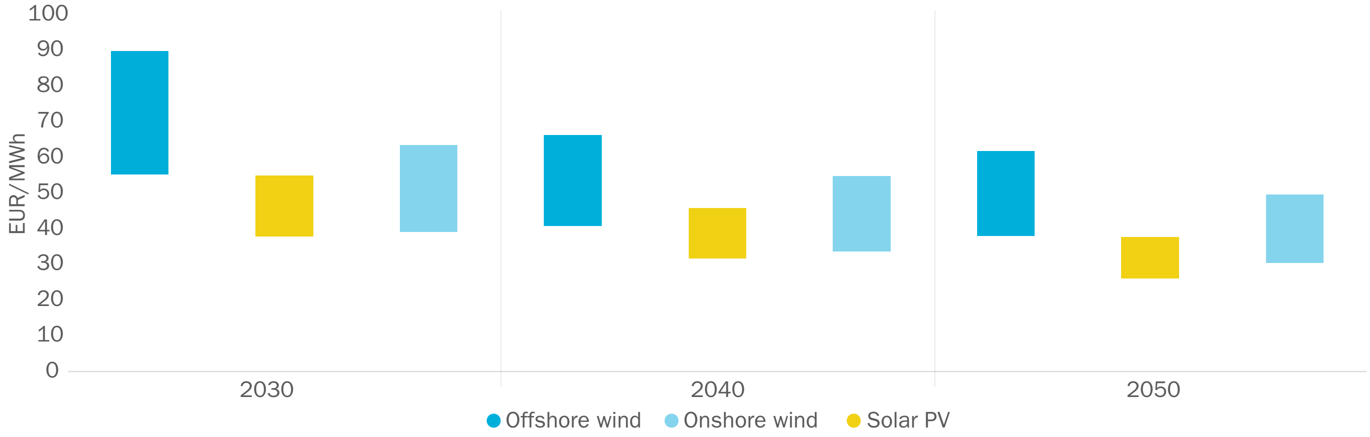
Our analysis shows that renewables are poised to replace fossil fuels, albeit at different rates and to different extents in the three scenarios. Over the next decade we will witness significant change in how energy is produced and consumed. In the Green Transition Scenario and Clean Tech Rivalry Scenario, renewable primary energy supply is projected to triple by 2050. The share of renewables in the energy mix is even higher when looking at final energy consumption due to the higher losses in processing and transporting of fossil fuels.[i] The Green Transition Scenario sees a more cooperative world where policy, markets and economics drive the rapid transformation of the energy systems. The Clean Tech Rivalry scenario is characterised by high competition and a push for independence from unreliable fossil fuel suppliers, propelling the growth of renewables. Even in the Delayed Transition Scenario, renewable primary energy supply doubles by 2050, primarily due to the cost-effectiveness of solar, wind power and batteries.

The future for fossil fuels, however, is bleaker. The historical pattern of GDP growth leading to increased fossil fuel use is set to break in all three scenarios. Coal usage is expected to be rapidly phased out in developed countries and subsequently in emerging economies, with the slowest phase-out in our *Delayed* scenario (Figure 9). In the *Green* scenario, developed nations phase out most of their coal capacity in the power sector by the 2030s, while developing countries will partially maintain theirs until 2050.

Oil demand, almost half consumed in the transport sector, is undergoing a shift in the Green Transition Scenario. Oil consumption is projected to be reduced by half by 2050. Even in the Green Transition Scenario, oil consumption persists to some degree in aviation and long-haul transportation. The petrochemical sector's growing share of total oil demand underscores the need for recycling to limit emissions. Oil plays a minor role in today's power system and is projected to be nearly phased out globally in this sector by 2040. In the Clean Tech Rivalry Scenario, the transition in the transport sector faces delays as clean vehicle supply chains struggle to adapt to a fragmented world with increased trade tariffs and barriers. Despite a slower pace, electric vehicles are still expected to replace internal combustion engine (ICE) cars. In the Delayed Transition Scenario parts of passenger transport are electrified. However, other transport segments experience minimal change, resulting in only a modest reduction in oil demand from current levels.

Gas consumption, like coal and oil, is predicted to decrease towards 2050, but at a slower rate. Gas will continue to play a role in maritime transport, blue hydrogen production, peak power supply, and as a fuel for switching from coal in industry and power. However, the Green Transition Scenario anticipates gas consumption starting to decrease from 2030. In the Green Transition

10 Technology costs of solar PV, onshore and offshore wind in Europe (LCOE, €/MWh, real'23).[ii]



Scenario, gas as peak power supply is projected to supply around 6% of global power demand by 2050, representing a 40% reduction from today's levels.

Nuclear energy generation grows across all scenarios, but not to the same extent as wind and solar PV. Despite being a zero-emission power generation source with significant potential, nuclear energy growth is hindered by costs, long lead times, regulatory hurdles, and the declining cost of renewables. In both the Green Transition and Delayed Transition Scenario, developed nations struggle to replace their ageing fleets, with the majority of new builds occurring in China and India. Meanwhile, the Clean Tech Rivalry Scenario, driven by a push for energy independence, forecasts a 150% increase in nuclear energy production by 2050.

Clean technology costs continue their downwards trajectory towards 2050

The cost of onshore wind continues to decline despite recent challenges. From 2010 to 2020, the cost of wind power fell by more than 30%, while during the last three years, onshore wind projects have gone through a period where costs have increased.[18] Many Western wind turbine manufactures have struggled financially due to higher raw material prices, inflation, rising interest rates, and fierce competition to make even larger, more powerful wind turbines. As a result, Western wind OEMs are embracing a slowdown in new turbine announcements, instead concentrating on simplifying and streamlining their portfolios, slowing the introduction of new products, and maximising the commercial lifespan of their existing offerings.

The recent rise in turbine costs will primarily impact projects commissioned between 2023 and 2025. We can already observe that turbine prices from Western manufacturers are plateauing and stabilising, and in the longer-term costs are expected to trend downwards (Figure 10). This is also driven by more normalised raw material prices and pricing competition between manufacturers as the industry returns to growth and a healthier financial state. In the Green Transition Scenario, levelised cost of energy (LCOE) is expected to decrease to about half of today's levels by 2050. However, in the *Delayed* Scenario, trade protection and more lasting financial struggles delay the expected cost reductions, leading to 60% higher costs than in the Green Transition Scenario. In all scenarios, onshore wind costs continue to decline long-term.

The still emerging offshore wind sector is going through a turbulent period. It is more expensive to construct an offshore wind project today than was foreseen in early 2023. Bottom-fixed offshore wind technology is a mature technology. However, the offshore wind sector is still emerging. For the last few years conditions have changed both in terms of cost of capital and inflation. Inflation has hit the industry particularly hard due to the high CapEx intensity. Costs have increased owing to

[i] Primary energy supply refers to the direct amount of energy at the source that has not been subjected to any conversion or transformation process. The report uses the IEA's calculation method taking 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. With the alternative BP conversion method, the relative share of renewables in primary energy would be significantly higher. The challenge of building enough renewable power to replace existing fossil fuels is therefore less than it may seem only looking at primary energy numbers.
[ii] The outcome space per technology reflects the different scenarios, various underlying solar or wind conditions across Europe and variations in grid costs and costs for floating vs. bottom-fixed offshore wind technology.

Location: Talayuela solar farm, Cáceres, Spain

high commodity prices, rising interest rates and strains in the global supply chain. Supply shortages have turned out to be longer lived. The supply chain is not as robust and well-developed as the onshore wind supply chain and there has been a greater cost increase. The limited availability of specialised vessels and equipment for installation and maintenance, lack of skilled professionals, complex logistics for manufacturing and transporting larger wind turbine components are some of the current main hurdles.

The year 2024 is crucial for the sector, with more than 50 gigawatts (GWs) planned to be auctioned in Europe alone. Several countries around the world are willing to foster offshore wind despite the current complicated situation. In Europe, defined national targets totalling over 350 GW are to be met by 2050. There are also high offshore wind ambitions in several countries, including the US, South Korea, Japan, China, Vietnam, Taiwan, and Brazil.

Despite recent inflationary pressures, costs are expected to decline long-term. This is due to increased developer experience, growing maturity in turbine technology, greater availability of vessels, and the expansion of supporting infrastructure such as ports and transmission capacity. CapEx was on average down around 40% from 2010 to 2021, before the sector's recent turbulence, which led to around 20% cost increases.[19] Looking ahead, CapEx costs are expected to peak and then gradually decline over the next few years, ending about 5% below today's cost levels by 2030. On average, European offshore wind projects remain less cost-competitive in comparison to onshore wind and solar PV in the horizon of the analysis, even if costs are expected to come down significantly to 2050 (Figure 10). In many areas globally, the best wind resources are where the sea-depth requires floating offshore installations. Floating offshore wind is a less mature technology with higher costs at present compared to bottom-fixed offshore wind. In the Green Transition Scenario, there is a break-through in floating offshore wind technologies towards the end of the 2020s, resulting in a steep growth of this technology and rapid cost decline.

Falling costs and short time-to-build make solar PV a frontrunner in the energy transition. The recent cost increases in renewable technologies, driven by inflated material prices and strained supply chains, has already begun to ease for solar panels and batteries. Raw material costs are mostly back to pre-pandemic levels. Other parts of the value chain, in some countries, still experience higher costs due to increased grid connection costs and competition for land area. Globally, project

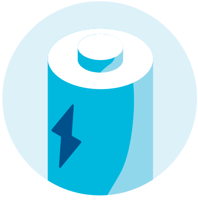
Declining costs and short build time make solar PV leading the way in the energy transition.

development activity is booming, with record capacity reached in China and Europe in particular, and high activity in India and the US. Manufacturers of input factors such as polysilicon, modules, cells and wafers are currently at overcapacity and some consolidation in the industry is expected.

Compared to other power producing technologies, solar PV has the shortest build time, a relatively predictable production profile and is flexible in terms of location. In all scenarios, a combination of utility scale and solar rooftop will be built. Dedicated solar farm facilities are typically the most cost-efficient but require more land than solar cells mounted on buildings. At the same time, solar cells on buildings often receive financial support and discounts on grid tariffs. Combining utility scale solar with agriculture (agrivoltaics) can alleviate some of the pressure on land use. However, this is currently somewhat more costly than utility scale solar PV plants.

By 2050, the levelised cost of energy (LCOE) for solar PV in Europe is expected to decline nearly 40% in the Green Transition Scenario. Though solar PV is a mature technology, it will still undergo rapid technological developments, leading to efficiency gains and cost reductions. The current PV supply chain is heavily dependent on China, and Chinese module production is increasingly competitive due to low inflation and over-supply of modules. In the *Green* scenario, the low-cost solar panels help solar power capacity to grow 11 times to 2050 globally compared to 2023 levels.

Protection of domestic manufacturing results in somewhat higher costs in the Delayed Transition Scenario until 2050 in other parts of the world outside of China. There is currently an increased focus on protecting domestic energy industry in many countries. For example, the European Commission recently launched several investigations into alleged unfair Chinese trade practices, including market-distorting subsidies for non-EU companies participating in European renewables auctions.[20] Despite these tensions, the deployment of renewables in Europe has not yet slowed. However, this does increase the risk of future supply chain disruptions and an escalation of tariffs, which increases the overall cost of the transition. In the *Delayed* scenario, protection of a domestic solar PV industry leads to higher module costs in Western countries compared to the Green Transition Scenario, and solar PV costs (LCOE) end up 45% higher in Europe.

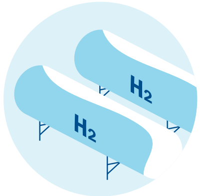


Battery energy storage costs have decreased by 90% since 2010.[21] There was a sharp decline in lithium costs in 2023, as the quick increase of lithium mining and refining reduced pressure on supply and demand. Lithium carbonate is the primary raw material for energy storage batteries (LFP) which are increasingly used in electric cars (EVs). As such, the supply and demand balance and cost development of battery storage are closely tied to EV sales. Key raw materials for batteries are sourced from a limited number of countries, leading to a vulnerable supply chain. In the Green Transition Scenario, the supply of lithium is expected to be adequate, while other battery types such as sodium-ion batteries or flow batteries, gradually gain market share, reducing pressure on supply. New chemistries can cause technology leaps in the energy storage industry. The commercialisation of sodium-ion batteries is in the process, and flow batteries are having a renaissance in China. Overall, the cost of batteries is expected to come down significantly towards 2050, with a more than 50% reduction in CapEx according to the Green Transition Scenario. This reduction is driven by new battery chemistries, mass production and more efficient supply chains.

Annual installed system storage capacity surged by a substantial 150% in 2023. This was largely driven by installations in China, as well as other markets, including Europe. Installed solar capacity is the primary driver for the increase in storage volume, both utility scale and small-scale solar. Currently, residential batteries make up over half of Europe's energy storage, fuelled by a surge in rooftop solar installations. The main driver in China is co-location of solar, wind and storage. Growth in battery energy storage is expected to continue in our scenarios. The Green Transition Scenario expects capacity to increase to more than 40 times from today by 2050. However, the exact volumes needed for energy storage depend heavily on volumes of other flexibility options like smart EV charging, demand side response, flexible hydropower, and clean hydrogen in the relevant power systems.

Co-locating solar or wind power plants and batteries will continue as this significantly reduces upfront CapEx. The main reductions are related to grid connection, transformer, and balance of plant (BOP) costs. Co-location can also reduce costs related to site preparation, land acquisition, labour for installation, permits, and developer overheads. In addition, OpEx savings are possible due to shared asset management, security, and land leasing. Additional cost savings are expected over time as grid costs comprise a larger portion of the total project cost.

Stationary energy batteries can play a key role in providing flexibility and system stability. Batteries can provide fast ramping as they can react immediately to imbalances in the system with a fast frequency response. They can also help balance the daily variability in solar PV by storing electricity in a few hours and reducing the solar PV peak supply to the grid during midday, thereby reducing the intraday price volatility. In this way, system batteries can facilitate more solar PV into the power system. For more details on flexibility needs and solutions, see page 59.



Cost of electrolyser plants are expected to fall significantly with increasing deployment, despite current inflation and supply chain constraints. Some recent cost increases are more cyclical, like higher cost of capital, high energy costs and supply chain bottlenecks. Those are expected to come down in the next few years. In the long run, large-scale deployment of electrolysers facilitated by policy will bring down costs. From today to 2050, the costs of a 100 MW electrolysis plant are expected to decrease in the range of 50% to 75% in our scenarios.

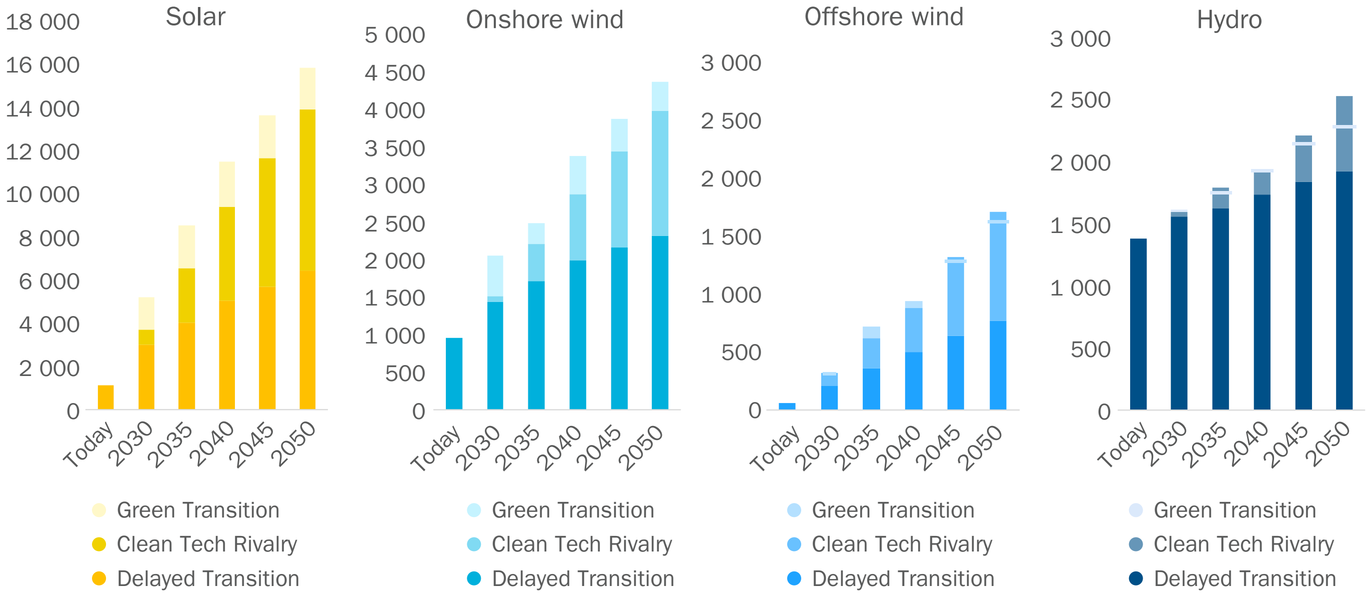
Development of a European hydrogen economy has seen a slow start. Several projects have been announced, but many final investment decisions have been pushed out in time recently. Even if electrolysers have been produced and operated for 90 years, they are made on a smaller scale and are therefore relatively expensive. In addition, the complete supply chains with hydrogen pipelines, filling infrastructure and larger storage facilities, need to be established. Support and incentive schemes will be required in a build-up phase in all parts of the hydrogen value chain, including research and development.

Hydrogen regulations are emerging across the European value chain and there is much more clarity on the rules today than one year ago. During 2024 the first auction from the EU Hydrogen Bank was conducted, providing up to 10 years of support for green hydrogen production projects. This is supplemented by other EU and national funding programs. A major milestone was the recently adopted EU Renewable Energy Directive III and its two Delegated Acts. The directive sets the first mandatory green hydrogen consumption obligations in transport and industry, while also providing a definition for green hydrogen (RFNBO).[i] Ambitions are high, a total 20 of 27 EU countries have in place a national hydrogen strategy (or roadmap) today, on top of the EU hydrogen strategy.[22]

[i] EU RED III sets binding RFNBO (renewable fuel of non-biogenic origin, such as hydrogen) quotas: At least 42% RFNBO of EU industry's total hydrogen consumption by 2030 and 60% by 2035. Two delegated acts are adopted, detailing specific rules for RFNBO production. On top, the FuelEU Maritime and ReFuelEU Aviation Regulations include specific quotas for hydrogen and synthetic fuels (RFNBO) in these sectors.

Co-locating of solar or wind power plants and batteries will continue as this reduces upfront CapEx by a significant amount.

11 Cumulative renewable power capacity globally from today to 2050 across scenarios (GW).



Renewable electricity exhibits strong growth across scenarios

Renewables are already the cheapest source of new energy, and costs are expected to further decline. The growth prospects of renewables are additionally supported by significant cost declines in batteries, which facilitates the integration of large renewable volumes into the energy system. According to the S-curve model for technology lifecycles, solar and wind technologies have left the emerging technology phase of exponential growth and have entered the mature technology phase seeing more steady growth in many countries.[23]

There is rapid but varying growth outlooks in renewables across the three global scenarios. The real winners of the energy transition in all scenarios are wind and solar power. In the Green Transition Scenario, their collective power output is projected to quadruple by 2030 and increase by an impressive 1300% by 2050, thereby transitioning from a minority power source to the dominant power supplier in 2050. In the Clean Tech Rivalry Scenario, the narrative is similar, but the phase-down of coal and the expansion of renewables are slowed to post-2030 due to reshoring of supply chains. However, significant momentum is regained from around 2040, with substantial investments in wind, solar power, and nuclear. As a result, solar and wind reach a share of 60% by 2050, with nuclear supplying more than 10% of the total global power demand by 2050. In the Delayed Transition Scenario, the energy transition is deprioritised due to other pressing issues, resulting in less traction. Despite this, renewable power generation still dominates capacity additions as they represent the cheapest new energy sources. However, the pace is slower than in the other two scenarios, and the phase-out of fossil fuels is more gradual. Ultimately, all renewable energy sources collectively supply 65% of global power demand in 2050, compared to 79% in the Clean Tech Rivalry scenario and 84% in the Green Transition Scenario.

Barriers are most visible in the Delayed Transition Scenario. Due to conflicting interests, opposition to the green transition slow down further capacity additions, and there is less political will to make land areas available compared to the Green Transition Scenario. Also grid operators struggle to integrate more intermittent capacity into the power grid as fewer resources are allocated for necessary grid upgrades and expansions, and permitting processes are slower. These obstacles are present in the Green Transition and Clean Tech Rivalry Scenarios as well, but to a lesser extent. The Delayed Transition Scenario is additionally characterised by high geopolitical tension, weaker GDP growth and slower decarbonisation of energy end-use. This results in less total electricity demand in comparison to the other scenarios, and therefore reduces the need for capacity additions across technologies (Figure 11).

In the Clean Tech Rivalry and Delayed Transition scenarios, supply chains for wind and solar adjust to an increasingly tense geopolitical landscape. The global trade of clean technologies remains strong in the Green Transition Scenario, resulting in high wind and solar build-out at a low cost. In the Clean Tech Rivalry and Delayed Transition Scenarios, near- and friend-shoring efforts resulting from additional trade protection measures delay capacity additions. However, large-scale developments of solar and onshore wind through to 2050 are featured in both the Clean Tech Rivalry and the Green Transition Scenarios. Offshore wind gains momentum after 2030 in both the Clean Tech Rivalry and the Green Transition

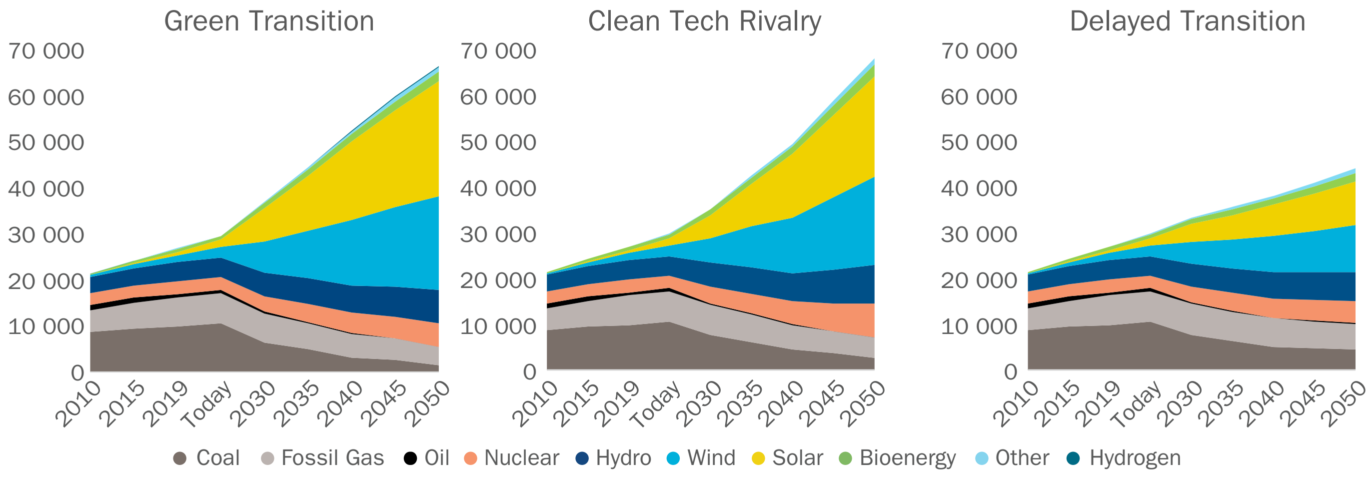
Location: Kjøllefjord wind farm, Finnmark, Norway

The real winners of the energy transition in the Green Transition scenario are wind and solar power. Their collective power output is projected to quadruple by 2030 and increase by an impressive 1300% by 2050.

Scenarios. Continued substantial investments and generous subsidies pay off over time and costs come down to competitive levels. Installed offshore wind capacity surpasses 1500 GW globally by 2050 in both scenarios, increasing from approximately 70 GW today. In the Delayed Transition Scenario, however, the initial momentum is dampened when policy push is reduced, subsidies are discontinued, and global volumes remain below 800 GW.

For hydropower, the primary limitations are the availability of suitable resources. This is in addition to the fact that a large share of global hydropower potential is already in production. Most new potential is in Asia and Africa, where high power demand is expected. The energy storage capabilities from existing hydropower reservoirs globally are unique, covering more than 1,500 TWh of energy today.[24] Hydropower is a highly valuable flexibility provider and a good match with more intermittent renewable sources. In the Green Transition Scenario, an additional 900 GW of capacity is projected to be built by 2050. Even greater capacity is predicted in the Clean Tech Rivalry Scenario, because hydropower is a relatively low-tech alternative without the same need for global supply chains as solar and wind. In the Delayed Transition Scenario, reduced energy demand decreases the need for additional hydropower build-out (Figure 11).

12 Growth in electricity generation globally from 2010 to 2050 across scenarios (TWh).



Clean electricity decarbonises transport, buildings, and industry

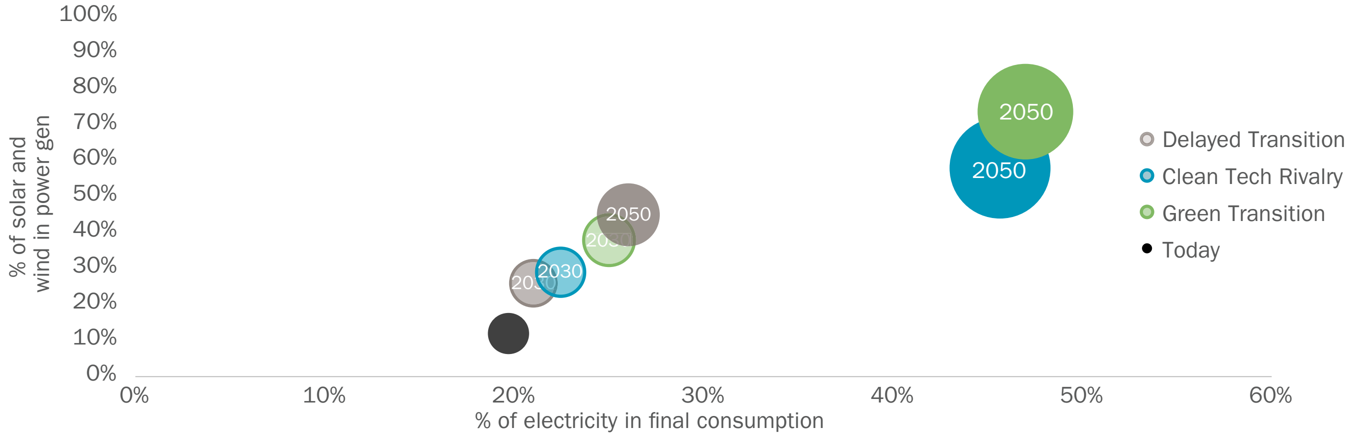
Current global power consumption totals approximately 29,000 TWh today. The electricity share in final energy consumption is around 20%. More than 60% of it is supplied by fossil fuels, about 9% by nuclear power and less than 30% by renewable energy sources.[25] With the current momentum of the energy transition, these shares in final energy, and also the total power consumption, will change significantly over the next decades. The increased electricity consumption from today to 2050 is also a result of continued global population growth, urbanisation and income growth. 80% of around 750 million people that lack access to electricity today are in Africa corresponding to more than 40% of the population.[26] In our analyses, we see the strongest electricity growth in India and the African continent, up more than three times from today to 2050 in the *Green* scenario.

The end use sectors in the Green Transition Scenario are largely decarbonising via three main pillars. The pillars are electrification with clean power, energy efficiency, and clean hydrogen for sectors that are difficult to electrify directly. There is also a role for bioenergy and carbon capture and storage. In simplified terms, this transition occurs in two phases. Initially, emissions are reduced primarily in the power sector, mainly through the deployment of wind and solar energy. From 2030, and partly in parallel, the use of clean power for electrification and the deployment of green hydrogen are accelerated, leading to a substantial increase in power demand.

In the Green Transition Scenario, electricity consumption increases by 79% in the industrial sector, 70% in the buildings sector, and 18-fold in the transport sector to 2050 (Figure 14). All of this is done in tandem with clear incentives for energy efficiency, recycling, material efficiency, more energy-efficient buildings, and a more efficient transport sector. Direct use of electricity is often far more energy efficient than fossil fuels – electric cars are typically three times more energy efficient than conventional ICE vehicles and heat pumps two to five times more efficient than gas boilers, contributing to roughly flat final energy consumption in 2050 compared to today. As a result, direct electricity use in final energy increases by 130%, growing from a share of 20% today to 47% in 2050. Clean hydrogen is primarily used in long-distance transportation and in the production of steel and chemicals, in addition to high heat in industry. Industry and transport account for, respectively, approximately 50% and 35% of the growth in clean hydrogen demand towards 2050. Therefore, global power demand already increases by 28% (to 37 000 TWh) to 2030 in the Green Transition Scenario, and to 67,000 TWh in 2050 (Figure 12).

The Clean Tech Rivalry Scenario follows a similar pathway, although electrification lags slightly behind the Green Transition Scenario due to the challenges of relocating supply chains in a world with rising geopolitical tensions. In this scenario, the focus is on building and protecting local supply chains, primarily through tariffs on imports from other countries, such as China. This leads to less efficient trade of materials and technologies that are key for the energy transition. In the short term, this makes clean technologies, like batteries and electrolysers, more expensive, which leads to slower deployment. Industry energy demand is significantly higher as capital is invested in building supply chains for clean technologies and onshoring production of key commodities like steel, which is quite energy intensive. A more subsidy-driven transition results in less incentive to reduce energy use. Less efficient choices (as compared to the globally more cooperative Green Transition Scenario) will entail a higher total energy demand leading to 7% higher final energy demand in 2030 and 2050. Reducing emissions will require more electricity and more clean hydrogen - 10% and 8% more respectively. This scenario also requires more fossil fuels, spread across all sectors, leading to

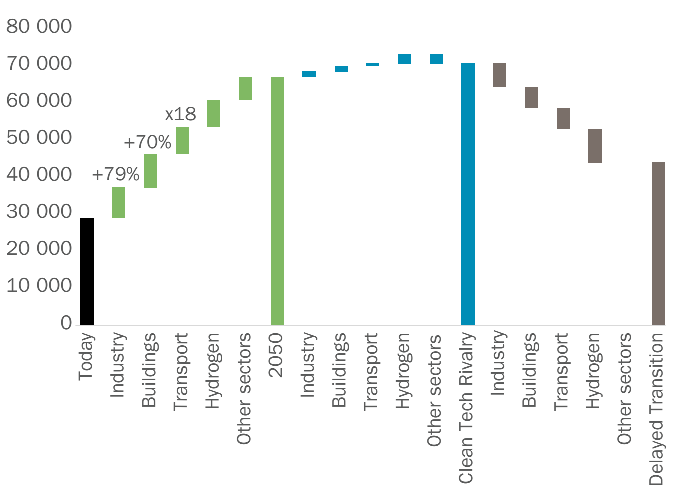
13 Share of solar and wind in total power generation globally (y-axis) and share of electricity in final energy consumption globally (x-axis). Size of circles reflect total power consumption (in TWh).



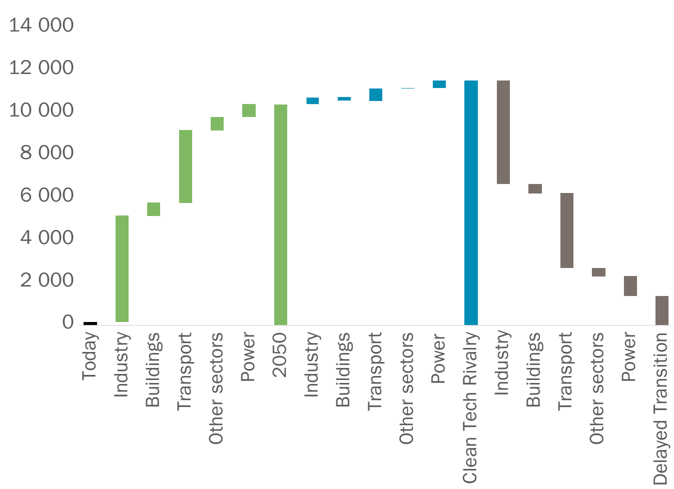
higher emissions and a more costly transition overall. Total power will increase by 134%, surpassing the total power demand of the Green Transition Scenario by 2050.

There are important differences between the Delayed Transition Scenario and the other scenarios in the end-use sectors. Lower GDP growth and weaker decarbonisation efforts lead to less power demand in the Delayed Transition Scenario. However, due to the lack of energy efficiency measures, 44,000 TWh of electrical energy are still required in 2050. While solar and wind remain cost-effective in the Delayed Transition Scenario, the electrification of end-use sectors depends more on policy initiatives and global cooperation and trade, particularly to achieve sufficient speed, cost reductions, and global deployment. The growth in power consumption is primarily driven by population and economic growth, while the decarbonisation of end-use is much less pronounced. This leads to almost one-third (23,000 TWh) less power generation in 2050 compared to the Green Transition Scenario. Increased protectionism leads to more energy-intensive growth, with fossil fuels maintaining a dominant role. Electricity's share of final energy consumption is 26%, which is 21 percentage points lower than in the Green Transition Scenario, while covering an almost 20% higher energy demand (Figure 13). Additionally, there is very limited deployment of clean hydrogen, other than replacing some existing use of fossil hydrogen in the chemical and refinery industry (Figure 15).

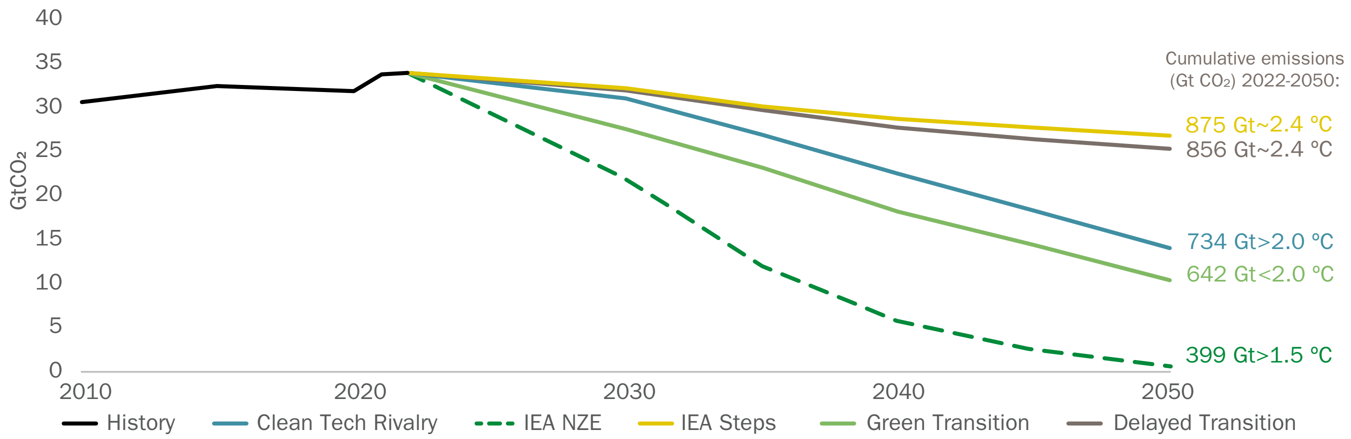
14 Change in electricity consumption per sector from today to the Green Transition-, Clean Tech- and Delayed Scenario in 2050 (TWh).



15 Change in clean hydrogen consumption per sector from today to the Green Transition-, Clean Tech- and Delayed Scenario in 2050 (TWh).



16 Total energy-related CO_2 emissions from 2010 to 2050 across scenarios and compared to the latest IEA STEPS and Net-Zero scenarios (Gt CO_2).[28]



Global CO_2 emissions to decrease even in a world with more conflict

According to the IPCC, global CO_2 emissions must be reduced quickly and reach net-zero by 2050 to limit global warming to 1.5 °C. To reach net-zero, any remaining CO_2 emissions must be offset by negative emissions, such as through carbon removal or uptake. To limit temperature increase to 1.5°C with a 50% likelihood, the remaining carbon budget is estimated to be 250 Gt CO_2.[i] With current emissions this budget will be spent within the next six years. This means that emissions must be reduced quickly or be compensated with even more negative emissions to stay within the budget. IPCC warns there are significant risks associated with emission pathways that rely on overshooting the carbon budget and later compensate with negative emissions. To restrict global warming to 2°C, the remaining carbon budget is almost five times higher at 1,200 Gt CO_2 from 2022 to 2100. The consequences of 2°C are expected to be far more severe than 1.5°C warming. These estimates are very sensitive to assumptions on other factors, including aerosols and other greenhouse gas emissions like methane and nitrous oxide, particularly concerning the 1.5 °C carbon budget.[27]

Other greenhouse gases, not only CO_2, must also be strongly reduced to reach the climate targets. There are significant emissions not related to the use of fossil fuels, such as methane and nitrous oxide from biological processes and fluorinated gases (HFCs and PFCs). The carbon budgets are heavily dependent on how much and when different types of non-CO_2 emissions occur. In the scenarios these emissions are not analysed specifically. Even if one succeeds in reducing these other emissions significantly, the scientific evidence implies that CO_2 emissions must be quickly reduced to reach net-zero.

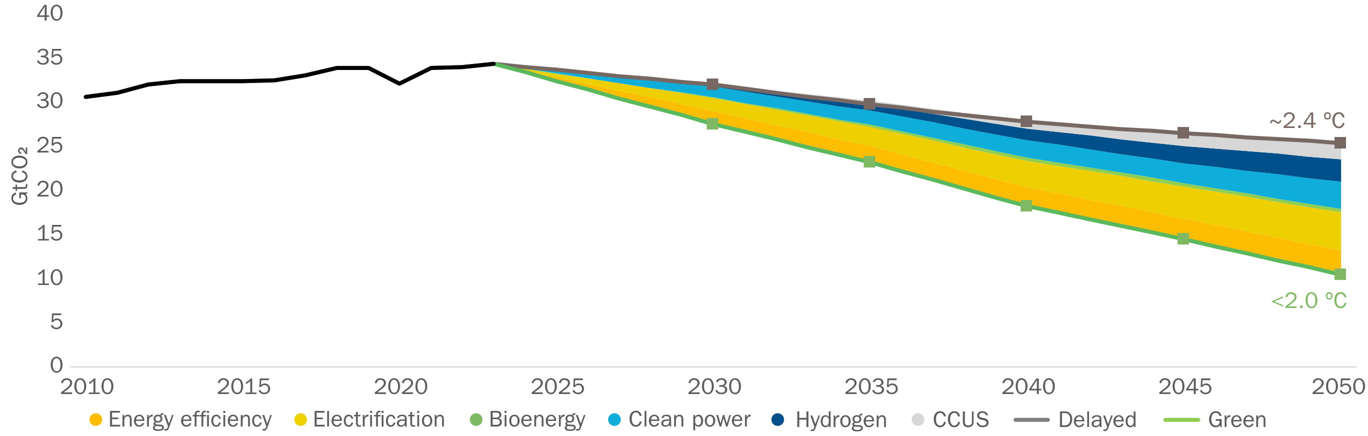
In the **Green Transition Scenario**, global energy-related CO_2 emissions are set to decrease relatively quickly, reaching around 10 Gt of annual emissions by 2050. This will be on a pathway to limit global warming to below 2°C in 2100 when compared with most recent IPCC scenarios, but by far exceeds the carbon budget for reaching the Paris Agreement target of 1.5°C and net-zero in 2050 (Figure 16). The expected temperature increase is also dependent on carbon removals and emission reductions continuing beyond 2050.

Despite efforts to implement new emission-reducing technology, **the Clean Tech Rivalry Scenario** lags behind the Green Transition Scenario and fails to catch up. Higher costs are expected to result in lower emission reductions in the short term. Increased global trade barriers lead to higher costs and less clean technology deployment, and higher energy demand makes emission reductions more challenging. In the long term, the transition is primarily focused on the developed world and China, and less energy efficiency is expected to result in higher emissions across the time horizon. Between now and 2050, cumulative emissions are projected to be 14% higher, and annual emissions in 2050 are expected to be 35% higher (Figure 16), likely leading to global warming exceeding 2°C. Considering the more pessimistic **Delayed Transition Scenario**, the power sector's transition, with wind and solar replacing coal and gas, leads to peak emissions within the next decade. However, the expected slow decarbonisation of end-use sectors leads to lower emissions reductions, especially towards 2050. This is consistent with a pathway of likely temperature increase of 2.4°C.

The differences in climate mitigation solutions between the Delayed and the Green Transition Scenario as shown in Figure 17 illustrate that all the major clean techs play a big part in reaching a Green Transition Scenario:

1. Increased electrification (29%), especially in the transport (8%) and industry sector (14%). Even though electrification is the most efficient way to reduce emissions in the end-use-sectors, its deployment remains relatively limited in the Delayed Transition Scenario.

17 Total energy-related CO_2 emissions from 2010 to 2050 for the Delayed and Green Transition Scenarios, showing the emission reductions per key climate mitigation solution (Gt CO_2).



The main differences are within industry and transport, where the emissions are most expensive to cut.

2. Energy efficiency or avoided demand (18%). The Delayed Transition Scenario is a less efficient world, with quite energy-intensive economic growth. To close the gap between this scenario and the Green Transition Scenario, less energy-intensive economic growth is needed. This is solved by more direct use of electricity compared to inefficient fossil fuels and more efficient use of energy across all sectors, including behavioural change and more circular economies.

3. Carbon Capture Utilisation and Storage (CCUS, 12%). CCUS is the most expensive and least mature solution for reducing emissions. In the Delayed Transition Scenario there is very limited CCUS as the policy push, the infrastructure build-out and the cost reductions needed are lacking. In the Green Transition Scenario, CCUS is mainly used in industry and power sectors, including carbon removals.

4. Clean hydrogen (17%). Hydrogen is also on the expensive side of the emission-reduction spectrum, and deployment is limited in the Delayed Transition Scenario. Thus, this is an important solution to close the gap from the Delayed Transition Scenario to the Green Transition Scenario, especially in some 'hard-to-abate' sub-sectors in industry and transport.

5. Bioenergy (3%). Bioenergy is an important part of the decarbonisation solutions. There is limited supply of sustainable bioenergy and most of this is already utilised in the *Delayed* scenario. Therefore, only around 3% of the additional emission reductions stem from more bioenergy going from the Delayed Transition Scenario to the Green Transition Scenario.

6. Clean power (21%). Even though there are substantial emissions reductions in the power sector in the Delayed Transition Scenario, even more is required in the Green Transition Scenario, and renewable technologies need to be deployed faster. This must happen in tandem with the significant growth in power demand.

[i] As of January 2023, according to IIASA. Using updated methodology and data since AR6 by the IPCC was released in 2022.

Bioenergy is an important part of the decarbonisation solutions.

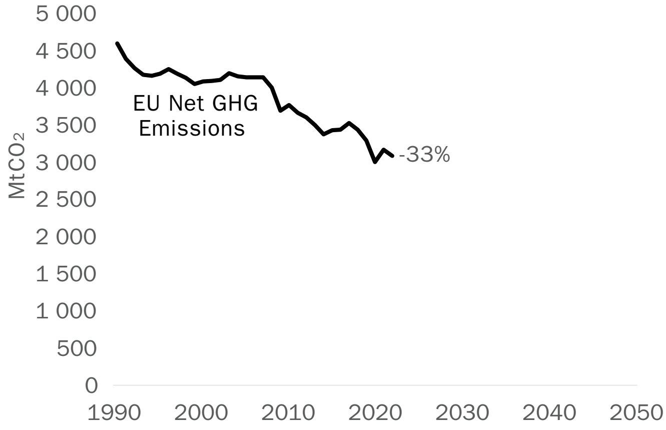
PART 3

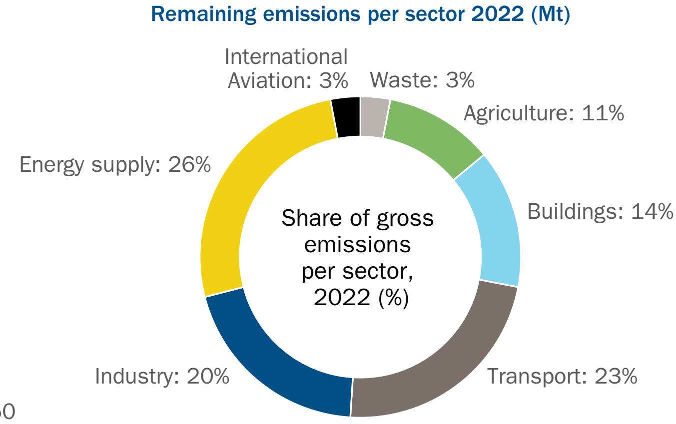
What's next for the European transition?

Europe's energy transition has already progressed significantly, and the EU has been a global champion of climate and energy policies. Since 1990, emissions have declined faster in the EU than in any other major economy. Amidst a new security situation and more fragmented political landscape, there is uncertainty related to the pace of the energy transition. Although economic constraints and the prioritisation of defence budgets could impact the speed of the transition, this transition is also urged by the need to strengthen Europe's resilience and improve its industrial competitiveness. In this chapter we look into how Europe's transition will evolve in two of the scenarios: Green Transition and Delayed Transition.

Location: Vinje hydropower plant, Telemark, Norway

18 Total greenhouse gas emissions in the EU from 1990 to 2022 (Mt CO2e) (left), emissions per key sector in 2022 (Mt CO2e, right).[32]





Changed drivers for the European energy transition

Balancing the needs for security, affordability, sustainability, and competitiveness

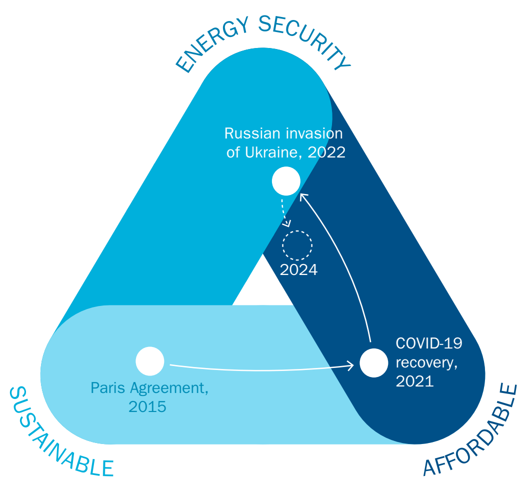
Despite several crises and extraordinary events in recent years, Europe's commitment to the energy transition remains strong. Also in Europe, the effects of global warming are becoming increasingly visible across the continent. Higher frequency of extreme weather, including droughts, wildfires, floods and storms, are impacting the economy in unpredictable ways, affecting crops, tourism, infrastructure, supply chains, and more. This has resulted in annual economic losses of 50-60 billion EUR over the past two years. Climate change remains among the top five concerns of EU citizens. When it comes to key priorities for the EU in the next five years, climate, along with security and defence, rank the highest, followed by health, the economy, and migration.[29]

The geopolitical landscape, the drive for strategic autonomy, and the need for increased competitiveness are fuelling a strong push for energy security and resilience. The detailed legislative framework as part of the EU's Fit for 55-package is essentially adopted.[30] Since this pack was launched in 2019, the EU has undergone a pandemic, Russia's invasion of Ukraine, the withdrawal of gas, and a subsequent energy crisis. The resulting inflation and rise in interest rates have slowed economic growth and increased cost-of-living levels. As a result, the Green Deal – the EU's comprehensive strategy for achieving climate neutrality – now places much greater emphasis on strategic autonomy, security, and industrial competitiveness. Also, there is an increased push for faster renewable build-out for security reasons. However, the subsidy-driven aspects of the energy transition will face tougher competition from other national priorities, as defence budgets in European countries continue to grow, and military support to Ukraine is expected to remain high for the foreseeable future. Nevertheless, adequate electricity generation to meet the industrial ambitions of EU and its member states remains a key priority. In March 2024, more than 1,000 industry organisations called for an industry deal in the EU to increase the availability to clean electricity, cross-border grids expansion for electricity and hydrogen, and more streamlining of regulations across the EU single market to strengthen the competitiveness of European industry.[31]

European GHG emissions are decreasing and decoupling from economic growth

Europe has been a global front-runner in climate action, setting ambitious climate targets and delivering emission reductions (Figure 18). So far, greenhouse gas emissions

19 The European energy trilemma - priorities are shifting over time.



2024

have decreased by one-third compared to 1990 levels (2022), while the economy has grown by approximately two-thirds in the same period. Despite economic growth and a stable population, emissions have declined faster in Europe than in any other major emitting economy, with the economy's energy intensity decreasing 32% since 1990. In addition, the EU has achieved a 10% reduction in carbon intensity, calculated as emissions per energy use. There has been a 40% decline in primary fossil fuel consumption, and a clear decoupling of energy from economic growth. With the European Climate Law adopted in 2021, the EU's 55% climate target for 2030 and net-zero target for 2050 are legally binding, meaning that the EU institutions and Member States are bound to take the necessary measures at EU and national level to meet these targets.

EU greenhouse gas emissions continue their downward trend. Net greenhouse gas emissions increased temporarily in 2021, up 4.8%, rebounding after the -3.7% dip during the COVID lockdowns in 2020. Since then, emissions have decreased annually; -1.4% in 2022 and -5% in 2023. This trend is in contrast to the increase in global emissions over the past two years.

The EU's share of global emissions has continued its downward trend since 1990, decreasing from around 15% in 1990 to around 7% today.[33] Moving forward, annual emission reductions must accelerate, doubling or even tripling the pace of the last decade, to achieve Europe's 55% target by 2030 and 90% target by 2040.[34]

Approximately three-quarters of EU emissions are energy related, and there are major differences in emission reduction levels across sectors and countries. The power and transport sectors are responsible for the largest share of gross GHG emissions in the EU, with, respectively, around 26% and 23%, followed by industry (20%), buildings, and agriculture (Figure 18). When it comes to net GHG emissions, the Land Use, Land-Use Change and Forestry (LULUCF) sector in the EU has reduced its carbon removal capacity since 1990, but it remains an important net removal source of about -210 Mt CO_2e in 2022. From 2005 to 2023, the energy supply and industry sectors have reduced emissions significantly, while transport, buildings, and agriculture have reduced at a much slower speed. To achieve the emission cuts needed to reach the 2030 and 2050 targets, the emission reductions in the transport and

The energy transition is governed with a variety of policy tools by the EU in all sectors, as reduced emissions are becoming increasingly relevant for all areas of the economy.

building sectors specifically must accelerate substantially, while power supply and industries must maintain a rapid decarbonisation pace.[35]

New priorities are changing Europe's energy and climate policies

Climate is integrated in all EU policy areas. The energy transition is governed by a variety of EU policy tools in all sectors, as reduced emissions is increasingly relevant for all areas of the economy. In addition to setting targets for emissions reduction, energy efficiency and renewable deployment, the European Commission is facilitating regional co-operation in areas where EU-level coordination is essential, such as in grid infrastructure projects and new funding mechanisms like the European Hydrogen Bank.[36]

Europe's dependency on China for the majority of components and input materials used in clean technologies has prompted the EU to seek greater resilience in critical supply chains. The EU's energy transition requires the accelerated deployment of clean technologies such as solar, wind, batteries, heat pumps, and electrolysers. The European Commission expanded the Green Deal in February 2023 to include an industrial dimension, called the Green Deal Industrial Plan.[37] Under its four pillars – regulation, financing, skills, trade – it aims to improve access to critical raw materials and net-zero technologies by scaling the manufacturing capacity of net-zero technologies in Europe and engaging in strategic partnerships with resource-rich countries, including Australia and Chile. Key regulations include the Net-Zero Industry Act and the Critical Raw Materials Act, which have now come into force and will be implemented in the coming years. With the re-election of European Commission President Ursula von der Leyen, these efforts are expected to be strengthened with the proposed 'Clean Industrial Deal', which is set to be introduced within the first 100 days of the new mandate.[38]

The Net-Zero Industry Act and the Critical Raw Materials Act each set indicative targets for domestic manufacturing and extraction.[39] This is supported by shorter permit timelines for both manufacturing facilities of clean technologies and extraction and refining facilities for raw materials. While the Green Deal Industrial Plan does not provide new funding, the EU has redirected existing

Location: Talayuela solar farm, Cáceres, Spain

funds, such as the Recovery and Resilience Fund, towards investments in manufacturing and further relaxed state aid rules under the Temporary Crisis and Transition Framework.[40] Several Member States have also taken steps to promote European-made components. In France, a new decree makes low carbon footprint a condition for electric vehicle subsidies, and the government has announced special auctions for rooftop solar PV, providing guaranteed offtake for two planned national solar PV factories. In Spain, new auction criteria that benefits local manufacturing was announced. In parallel to the scale-up of new domestic industries, existing industries are undergoing ambitious decarbonisation processes.

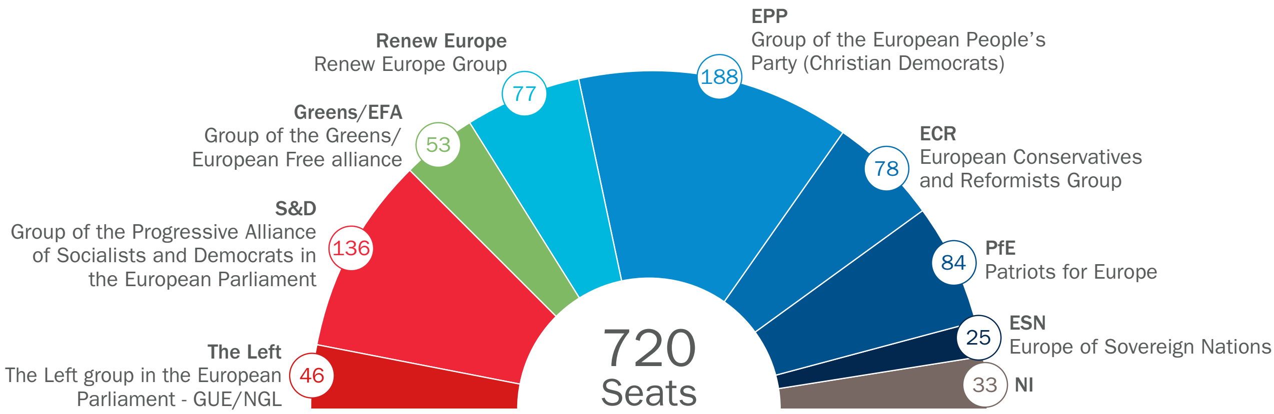
EU institutions, despite facing multiple crises, have managed to adopt most of the legislation introduced by the von der Leyen Commission. The Fit for 55-package has put the EU on a path to achieve its targeted 55% emission reduction by 2030. The next phase will require efficient implementation by Member States, including a new permitting framework for renewables with shorter deadlines for permitting processes under the revised Renewable Energy Directive (REDIII).[41] In addition, new targets have been set for industry and transport consumption of green hydrogen and an increased target for energy efficiency. Significant national efforts are required to decarbonise sectors like transport and buildings - major countries such as Germany, France and Italy are important for the EU to reach its goals. Just and equitable transition has moved higher on the agenda, while opposition to policy measures that drive up costs is growing. Measures that alleviate this are key to avoiding reversal of effective implementation.

A key challenge for the EU is addressing the required investment for the transition, estimated to be €1.5 trillion annually from 2031 to 2050. The COVID-19 pandemic, the energy crisis, and civilian and military support for Ukraine have necessitated hundreds of billions of Euros in unforeseen public funding, pushing several Member States beyond sustainable debt limits under the EU fiscal pact. Additionally, the upcoming EU budget period is expected to introduce significantly higher borrowing costs compared to 2019. By 2025, the EU is expected to phase out temporary State Aid flexibility, and the Recovery and Resilience Fund expires in 2026.[42] Preparations for the next seven-year budget are also underway, and Ursula von der Leyen has announced a new 'European Competitiveness Fund' to invest in strategic technologies such as clean industry and artificial intelligence. To meet its financing needs, Europe must find ways to mobilise private and public investments for a sustainable and competitive economy. A coordinated approach, including joint debt issuance, an expanded European Investment Bank mandate, and the mobilisation of national banks and pension funds, is being considered to reduce fragmentation, and prevent regional imbalances.

In line with the Paris Agreement, the EU will need to set its 2040 climate target no later than 2025. In addition to ensuring that the EU is on track to achieve its 2030 targets, the Commission is currently preparing to deliver the 2040 framework. In February 2024, the previous Commission proposed a 90% GHG emissions reduction target for 2040, which will also shape the EU's NDC pledge for emissions reduction by 2035.[43] Ursula von der Leyen has vowed to support this target under her new mandate. The legislative package to achieve the climate target is expected to be introduced by mid-2026. While carbon pricing is expected to remain a key policy tool, political shifts in the Parliament and Member States, coupled with a growing focus on industrial competitiveness, security concerns, and social impact, indicate there will be greater emphasis on complementary policies moving forward.

Implications on climate and energy policies from the EU elections in June 2024

20 European election results, European Parliament 2024-2029.



The EU elections were held from 6-9 June 2024, resulting in the election of 720 Members of Parliament for the 2024-2029 parliamentary cycle. The pro-European coalition maintained its majority, with the conservative European People's Party and the Social Democrats remaining, respectively, the largest and second largest parties, supported by the liberal Renew group and the Greens. Although the expected shift to the right was smaller than anticipated, the Parliament saw an increase in right-wing representation, growing from two to three political groups, with the newly formed 'Patriots for Europe' becoming the third-largest party.[44]

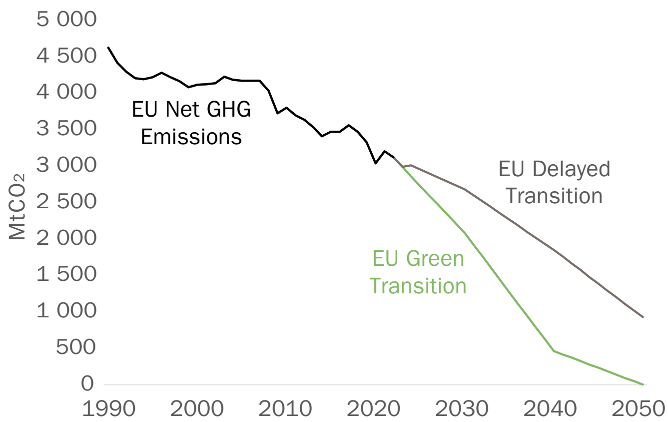
Despite these changes, the EU is not expected to reverse its commitment to the green transition, as the majority of political groups support continued climate efforts and the ambitious 2040 targets. However, the political shift towards the far right, both in the Parliament and in some Member States, will influence the EU's agenda and policymaking. Increased fragmentation within Parliament could make it more challenging to secure the broad majorities required to pass larger initiatives that are essential to the transition. This fragmentation could also slow down regulatory processes and result in dynamics more like those in several national parliaments.

The election also led to the re-election of Commission President Ursula von der Leyen for the next five-year term. Following the election, the President presented her political priorities for the upcoming mandate. These included a firm commitment to the Green Deal and a renewed focus on transitioning away from fossil fuels and decarbonising industry as means to enhance both the economy and security, reinforcing the Green Deal as a growth strategy.

Green Transition

Delayed Transition

21 Net greenhouse gas emissions in the EU from 1990 to 2050 historically and for the two scenarios (Mt CO_2e).[46]



Introduction to the European energy scenarios towards 2050

The EU has set ambitious targets for the clean energy transition, industrial revival and energy resilience. All technologies are in place for a swift transition, but the political uncertainty, both internally in the EU and externally, is significant. Against this backdrop, it is valuable to examine the direction of the European energy transition. To explore this, we analyse two scenarios for European energy transition towards 2050, the Green Transition Scenario and the Delayed Transition Scenario.

The most rapid energy transition takes place in the Green Transition Scenario (*Green*) where climate action, coupled with industrial growth and energy security, remain top priority issues for policymakers and EU citizens. In this scenario, EU member states are able to speed up the transition and the EU reaches its 55% target by 2030 - as well as its proposed 90% target in 2040 and the net-zero target in 2050. In this scenario, the current EU legislation is efficiently implemented at national levels. This puts Europe on course to reach net-zero. In addition, the post-2030 energy and climate framework is detailed and adopted in a predictable manner over the next three to four years. The EU is strongly unified. We view this scenario as more likely and easier to achieve in a world with relatively high global trade, lower geopolitical tensions, and stable economic growth. In this scenario, global tension remains, but the relations between major powers are based on agreed-upon rules, and there is global cooperation on key issues such as climate change. The EU develops in a direction where markets, citizens, technology, and politicians largely move along similar lines, which in turn minimises transition costs. In this scenario, higher global volumes of clean technologies and efficient global trade result in overall lower clean technology costs. More efficient markets, combined with a predictable regulatory framework, lead to more rational investments and asset operations. Finally, a higher degree of trust and co-operation within Europe result in better use of energy across borders.

However, several potential hurdles could slow the transition, as reflected in the Delayed Transition Scenario (*Delayed*). One such hurdle is the economic outlook and fiscal balances. The Delayed Transition Scenario illustrates a situation in which the EU's fiscal room is strongly limited and other priorties than climate are higher on the agenda. In addition, greater geopolitical tension and more restrictive trade barriers will hinder access to essential clean technologies and key inputs for the green transition in this scenario, resulting in a slower transition and added costs. Different EU policy priorities will have a major impact on emission pathways. In the *Delayed* scenario, there is resistance to certain green policies, particularly those that are costly or negatively impact people's lives, with increased local opposition to climate mitigation measures. In this scenario, global trade becomes more disrupted and less efficient, economic growth slows, and the focus on energy efficiency declines as priorities shift towards defence, employment, cost-of-living, and security. Europe must invest time and money into rebuilding parts of its supply chains, resulting in a slower and more expensive transition. In this scenario, the EU only reaches emission reductions from 1990 levels of 42% by 2030 and 80% by 2050 (Figure 21). For more detailed description of the methodology and key assumptions see Annex 1.

In both scenarios, we examine energy-related CO_2

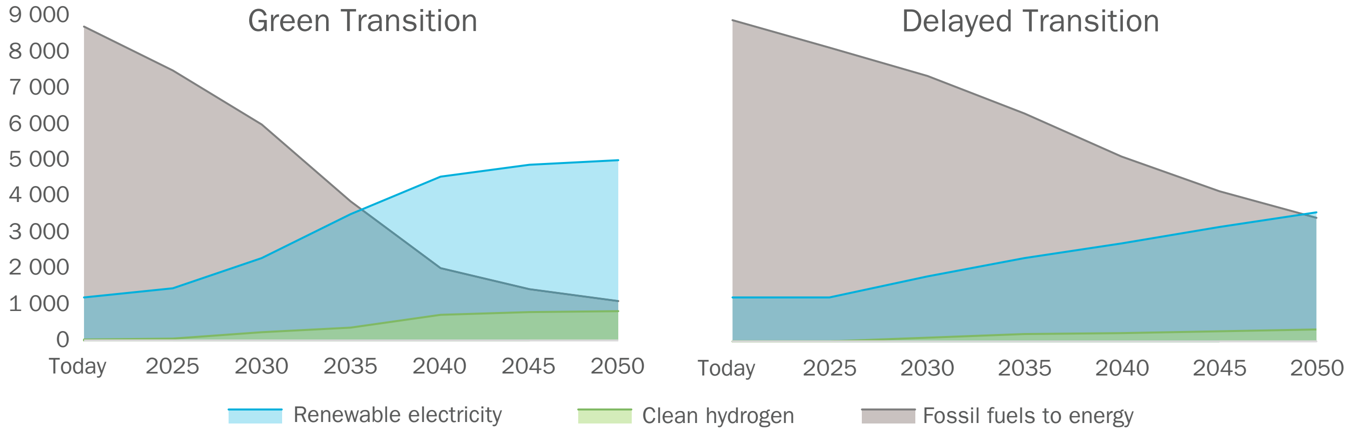
CO_2 emissions are currently responsible for around 78% of greenhouse gas emissions excluding emissions and removals in land sectors.

emissions and process CO_2 emissions in the cement, steel, chemicals, and refineries sectors. CO_2 emissions currently comprise around 78% of greenhouse gas emissions, excluding emissions and removals in land sectors.[i] Energy-related CO_2 emissions constitute a major part of CO_2 emissions, but there are also CO_2 emissions from industrial processes. Non-CO_2 emissions in the two European scenarios are based on the EU 2040 Impact Assessment.[ii,45]

[i] Methane, N2O and F-gases are responsible for 13.5%, 6% and 2.3% respectively. In addition, there are emissions and removals from land use and land use changes.

[ii] For the Green Transition Scenario data for LULUCF from the EU 2040 Impact Assessment Scenario S3 is used as input, while the Delayed Transition is based on scenario S1.

22 Energy supply across key fuels and energy carriers from today to 2050 (TWh). Primary energy for unabated/abated gas, oil and coal and energy production for electricity and hydrogen.



The European energy system: its current state and scenario results to 2050

Europe has been a front-runner in renewable energy deployment and climate change mitigation, but to reach the ambitious targets in the coming decades the energy transition must accelerate, and end-use sectors must contribute more than before. The following chapter presents the state of the European energy system and our model scenarios analysis to 2050.

Redesign of the energy system: Electricity replaces fossil fuels as the main energy carrier

For more than a century, fossil fuels have been the main sources of energy in Europe. During the next two decades, this dominance will come to an end.

Electricity consumption doubles by 2050 in the Green Transition Scenario. This is as a result of a swift shift from fossil fuels to direct electricity - such as electric cars and heat pumps, and growing electricity demand from green hydrogen and new industry activities such as data centres. Simultaneously, more efficient technologies and appliances contribute to limiting electricity demand growth and electricity growth flattens after 2040 (Table 1, Figure 22). In our Green Transition Scenario, final energy demand is reduced by 36% to 2050 due to high uptake of electric cars, heat pumps, energy efficiency measures and behavioural change such as increased car sharing and use of public transport.

Even in the Delayed Transition Scenario, electricity consumption increases by 50% by 2050 (Figure 22). Average annual demand growth rate is 2.8% and 1.7% from today to 2050 in the two scenarios, which is far above historic compounded annual growth rates of 0.3% from 2000 to 2022.[47] The modelling result illustrates that replacing fossil combustion with direct use of clean electricity very often is the cheapest and most efficient way to reduce emissions. Even in the *Delayed* scenario, final energy demand is reduced by 20% to 2050 compared to 2019. As a result of electrification, the

Table 1: Electricity consumption per sector for the *Green* and *Delayed* scenarios (TWh).

Green				*Delayed*			
Power consumption				**Power consumption**			
TWh	**2030**	**2040**	**2050**	**TWh**	**2030**	**2040**	**2050**
Buildings	1730	2100	2050	Buildings	1530	1690	1820
Industry	820	1410	1460	Industry	810	920	1140
Power, heat and e-fuels	430	770	850	Power, heat and e-fuels	210	290	340
Transport	220	740	940	Transport	160	390	600
Total	3200	5000	5300	Total	2700	3300	3900

Table 2: Clean hydrogen per sector for the *Green* and *Delayed* scenarios (Mt H_2).

Green				*Delayed*			
Clean hydrogen consumption				**Clean hydrogen consumption**			
Mt	**2030**	**2040**	**2050**	**Mt**	**2030**	**2040**	**2050**
Buildings	0.0	0.0	0.0	Buildings	0.0	0.0	0.0
Industry	3.1	14.6	15.9	Industry	1.9	4.3	5.6
Power, heat and e-fuels	1.1	3.2	5.7	Power, heat and e-fuels	0.5	2.0	2.3
Transport	2.6	4.1	3.8	Transport	0.9	1.3	3.0
Total	6.8	21.9	25.4	Total	3.3	7.6	10.9

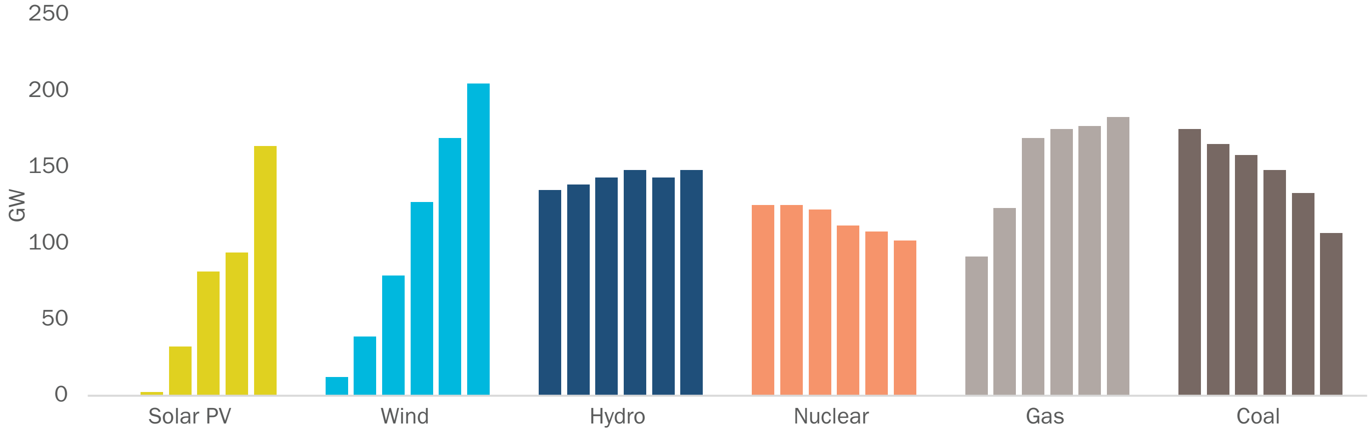
power sector becomes larger and more closely interlinked with other sectors, and therefore also increasingly fundamental from a security perspective.

Clean hydrogen expands manyfold to 2050, though from a low starting point. Currently, Europe consumes annually around 8 Mt of fossil hydrogen in the chemical industry and refineries.[48] Even with the substantial growth in clean hydrogen, our Green Transition Scenario falls 32% short of EU's domestic REPowerEU hydrogen target of 10 million tonnes by 2030.[49] In the Green Transition Scenario, the EU's total green and blue hydrogen consumption reaches 6.8 Mt by 2030, the vast majority of which is green. These volumes increase to 25 Mt by 2050. In the Delayed Transition Scenario, volumes are significantly lower (Table 2). Of the 3 Mt hydrogen produced in the EU in 2030, approximately 60% is used to replace today's grey hydrogen in the *Delayed* scenario. Electricity demand from electrolysis accounts for 13% and 7% of total electricity demand, respectively in the *Green* and *Delayed* scenarios in 2050. Electrolysis is used to produce both hydrogen gas as well as synthetic liquids.

The EU reaches peak fossil fuel consumption in energy in the coming years (Figure 22). Gas is still a vital component of the European energy system today, used primarily for heating in industries and buildings and as a flexible power source. It has helped reduced EU emissions since 1990 by replacing coal, particularly in the power sector. As the cleanest fossil fuel, gas will also be important going forward. In the power sector, coal is phased out of the mix before 2035 in the Green Transition Scenario - driven by exit policies - while strong renewable growth reduces total demand for gas.
In buildings, there is a strong fuel switch from coal and gas to electricity, mainly in the form of heat pumps.

In the transport sector, oil use in the passenger vehicle segment is quickly replaced by electricity, while the shift to clean fuels happens more slowly in the other transport segments. Finally, in industry, oil is phased out, coal is replaced by a mix of bioenergy, electricity, and clean hydrogen, while gas consumption decreases by around one quarter to 2035, declining even more rapidly thereafter. Bioenergy for space heating declines in both scenarios, as clean electricity replaces firewood and wood pellets. Instead, bioenergy use is shifted to applications that are hard to decarbonise, such as heavy transport and some industrial processes. We conducted a sensitivity analysis that opens the possibility for more import of sustainable biomass and biofuel at reasonable cost. This increases the use of bioenergy significantly, by 47% and 13% compared to the *Green* and *Delayed* scenarios, respectively, by 2050, for primary use in transport and industry. The increased quantities of imported bioenergy replace 2% of electricity and 39% of hydrogen in the *Green* scenario. This highlights the potential of bioenergy, but usage at that scale would likely fail to meet sustainability criteria given current expectations of global sustainable bioenergy demand. In 2050, electricity represents between 42% and 66% of total final energy demand in the EU, clean hydrogen 4% to 11%, bioenergy 12% to 16%, and fossil fuels 3% to 31% across the two scenarios.

23 EU installed capacity every five years from 2000-2020 and 2023 (GW).[50]



Renewables: Growing at an unprecedented rate, driven by lower costs

For the first time, wind power exceeded gas power generation in the EU, renewables provided 44% of total electricity production in 2023 and more than one quarter came from solar PV and wind power. Towards 2050, solar PV generation grows eight times while wind generation sees a growth of five times from today in the Green Transition Scenario. The electricity sector becomes fully decarbonised by 2050, with a renewable share in the electricity mix of 87%. Gas power remains an important flexibility provider, but the gas plants become emissions-free by 2050, and running hours decrease. Even in the *Delayed* scenario, solar grows five times and wind almost four times to 2050.

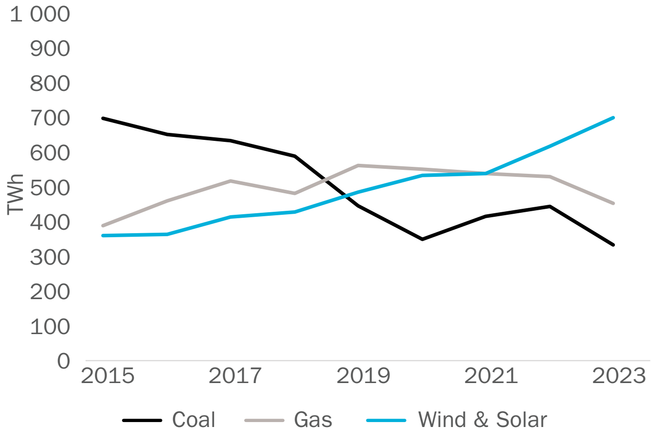
RENEWABLES - RECENT TRENDS AND THE CURRENT STATE

EU's renewable electricity generation grew to an all-time high 44% share of total electricity generation in 2023. Wind power surpassed gas and coal power generation for the first time ever, while solar generation increased by 18% year-on-year (Figure 25). In the EU, a record 56 GW of new solar PV capacity, 13 GW of onshore wind, and 3 GW of offshore wind were installed in 2023 (Figure 23).[51]

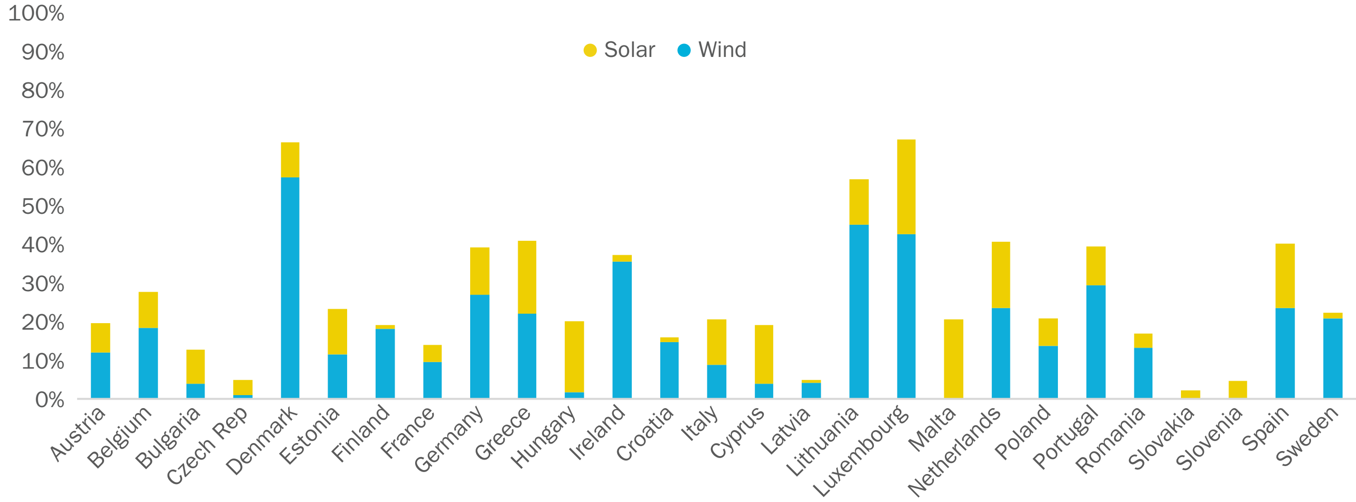
Throughout 2023, renewable electricity generation on average outpaced fossil electricity generation by 52% across Europe.[i] At the same time, utilisation of Europe's coal and gas power fleet decreased during the year to 34% for the coal power plants and 22% for the gas power fleet, respectively, down from 45% and 27% in 2022. Solar and wind power generation increased by 84 TWh.[53] There are major national differences in terms of the power mix and share of renewables (Figure 24). Denmark has the highest wind share at 58%, while Poland still relies on more than 60% coal in their power mix. France and Germany represent the two largest power sectors, producing around 500 TWh per year. They are followed by Italy and Spain at around 260 TWh per year. Italy currently relies on 45% fossil gas, and France has 65% nuclear in its power mix. In 2023, seven European countries reached a wind and solar generation share at or above 40%, while three countries still have a wind plus solar share at or below 5%.[54]

[i] This includes EU27, Norway and Switzerland.

25 Development of coal, fossil gas, wind and solar power generation (TWh) in EU27 from 2015-23.[52]



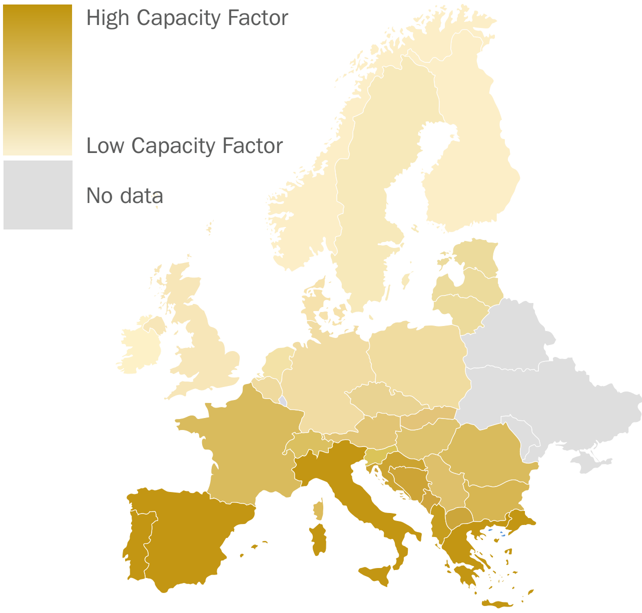
24 Solar and wind share of total power generation in the EU in 2023 (% of total TWh).[55]

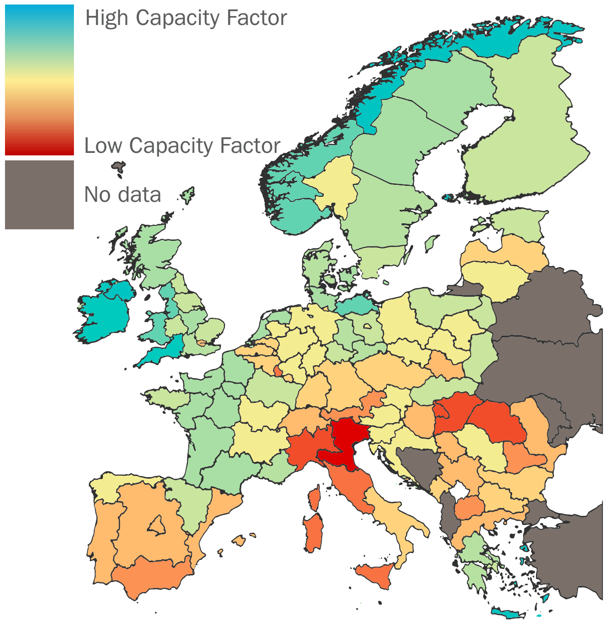


Location: Stamåsen wind farm, Jämtland and Västernorrland, Sweden

EU's renewable electricity generation grew to an all-time high 44% share of total electricity generation in 2023. Wind power surpassed gas and coal power generation for the first time ever.

26 Solar (left map) and wind (right map) resources across European regions, capacity factor (in %).

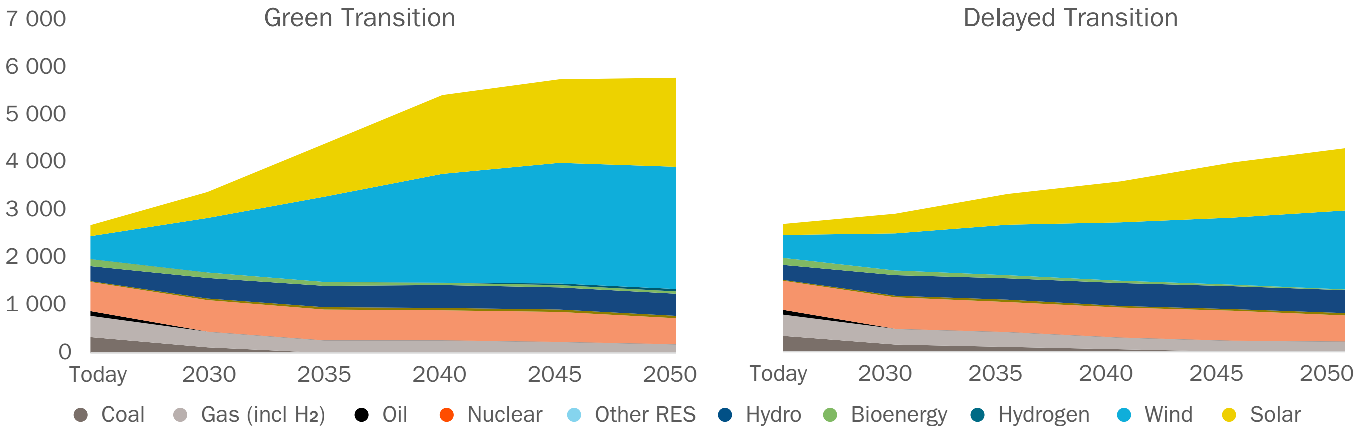




Power supply is rapidly transforming despite turbulence in recent years. In 2022, emissions in power supply increased by 3%, as the extreme gas prices combined with low nuclear and hydropower output increased the running hours of coal power plants. This increase was counterbalanced by strong growth in wind and solar power and was short-lived. During 2023, gas prices dropped from the extreme levels, output from nuclear and hydropower normalised, and we witnessed strong growth in wind power and solar PV capacity. These factors combined led to a record 19% emissions decline in the EU power sector in 2023.[56]

The EU benefits from particularly good wind resources in the north, while solar resources are significantly better in the south (Figure 26). We expect high growth in intermittent solar power along with short-term flexibility solutions in southern Europe, as solar resources are typically more effective in proximity to the equator. Further north the solar resources typically decline, but wind resources generally perform better in northern regions (Figure 26). There are significant differences between wind and solar power profiles. Due to the temporal complementarity of the two technologies in many countries, it is beneficial to have a mix of the two technologies in the power system. Solar power variations are often more predictable during the 24-hour day and over the season than wind power variations. Periods with high wind typically build up over time and can persist for several days, or even weeks. Wind power production is higher in winter than summer. Solar power production can rapidly shift from zero to full capacity, and its capacity factor is generally lower than that of wind power, typically ranging from 10% to 25% in Europe. In contrast, onshore wind has a capacity factor that is roughly double that of solar PV, with new onshore wind sites in Europe seeing capacity factors between 30% and 45%, while offshore wind is steadier and has typically a higher capacity factor of more than 50% for new sites.[57] Overall, there are significant variations in

27 Power production mix in the EU27 from today to 2050, (TWh).



capacity factors across different European countries and sites (Figure 26).

RENEWABLES IN OUR SCENARIOS TO 2050

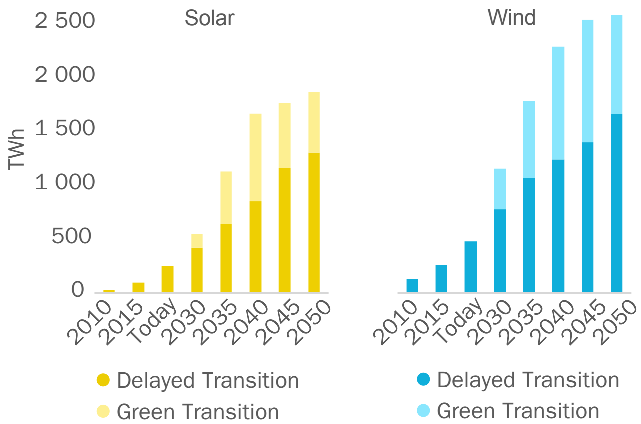
We expect and assume the cost reductions of wind and solar power to continue in Europe towards 2050 (see p. 18-21). Offshore wind is projected to experience the largest cost reductions, and the best areas will increasingly compete cost-wise with onshore installations towards the mid-century.

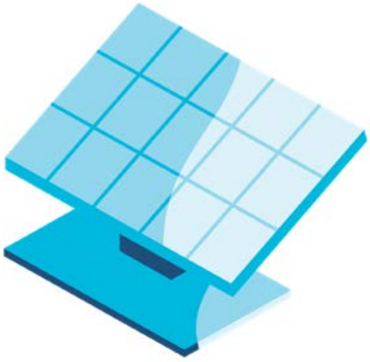
Solar PV and wind power are winning technologies across the modelled scenarios, driven by declining costs and the need for emission reductions. Solar PV capacity reaches 850 GW accumulated capacity in 2035 and 1360 GW in 2050 in the Green Transition Scenario. This is enabled by low costs, short lead times, and versatility in terms of location. Rooftop installations are expected to comprise around half of new solar capacity, facilitated by regulations and incentives in many EU member states. The remaining utility scale plants are expected to be built with and without trackers and mostly co-located with stationary batteries. In the Green Transition Scenario, wind power reaches a total cumulative capacity of 700 GW and 1000 GW in 2035 and 2050, respectively, compared to 440 GW and 660 GW in the Delayed Transition Scenario. Offshore wind currently plays a minor role in Europe's electricity mix, but the political targets for its growth are ambitious. In our scenarios, growth in offshore wind capacity rapidly accelerates after 2030, the result of ambitious offshore wind targets, falling costs, and improved supply chains.

Compared to current levels, solar PV generation grows eight-fold (five-fold) by 2050 while wind generation sees a five-fold growth (four-fold) in the Green Transition Scenario (*Delayed*), (Figure 27 and 28). The share of wind and solar in the generation mix increases to 41% and 50% in 2030, and to 69% and 77% share in 2050 for the *Delayed* and *Green* scenarios, respectively. Even in the Delayed Transition Scenario, the significant growth in renewables is enabled by wind and solar power's economic competitiveness and facilitated by policies such as the EU Wind Power Action Plan and the Renewable Energy Directive.[58]

The electricity sector is fully decarbonised by 2050 in the Green Transition Scenario. Gas power remains an important flexibility provider across scenarios, but the remaining gas power fleet becomes emissions-free before 2050 in the Green Transition Scenario, fuelled mainly with clean hydrogen and some fossil gas with carbon capture and storage (CCS). Gas power plants gradually shift to being flexibility providers and their operating hours are significantly reduced. The electricity sector decarbonises in parallel to a strong growth driven

28 Wind and solar power generation (TWh) from 2030 to 2050.





A high share of solar PV in the electricity mix will require a parallel development of short-term (24 hours) flexibility solutions.

by greater electricity demand from electrification in transport, buildings, and industry. In our Green Transition Scenario, electricity generation more than doubles by 2050, and the share of renewables in the electricity mix increases to 67% in 2030 and 87% in 2050. Hydropower is currently the second largest source of renewable energy with 317 TWh produced in 2023. By 2050 total hydropower generation increases by 49% in our *Green* and *Delayed* scenarios. Nuclear generation in the EU remains close to current levels in our scenarios, as new nuclear units will partially offset the decommissioning of existing ones. This aligns with many other analyses.[59] A sensitivity analysis assuming a stronger nuclear policy push in some member states and lower technology costs, results in capacity increasing by around 20% to 2050. Although more nuclear capacity is built in this case, the capacity factor for nuclear is reduced over time with more intermittent renewables. Coal and lignite power plants are phased out of the power mix due to exit policies in many countries.

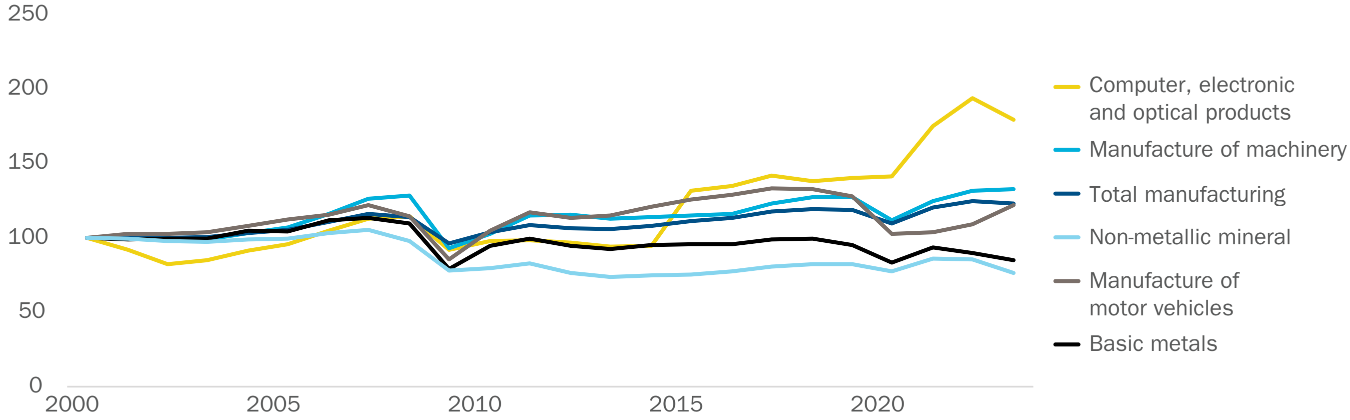
The parallel development of renewable electricity and flexibility solutions is key for a rapid transition and energy system resilience. A high share of solar PV in the electricity mix will require the gradual development of short-term (24 hours) flexibility solutions. These include stationary batteries, cross-border interconnections, smart and flexible demand from electric vehicles, heat pumps, and eventually electrolysers. A parallel development of solar PV and flexible solutions will enable a faster and more seamless expansion of solar PV. This supports the business case for solar PV and reduces the risk of boom-bust cycles for the industry.[i] Electrification of heating and the higher share of intermittent solar and wind power generation increase the weather and climate dependency of the power systems. This requires greater flexibility in other parts of the energy system ranging from within seconds to between years. While challenging, it is achievable. For more details on the flexibility challenge, see page 59.

[i] An uneven, fast build out of either flexibility solutions or intermittent power generation in a power system increases the cannibalisation effects of either the RES assets or the flexibility solutions.

Solar power production can rapidly shift from zero to full capacity, and its capacity factor is generally lower than that of wind power, typically ranging from 10% to 25% in Europe.

Location: Cabrera solar complex, Alcalá de Guadaira, Seville, Spain

29 Development in industrial production for key sectors from 2000 to 2023, indexed to 2000.[62]



The industry sector: A variety of outlooks and solutions for the transition

EU's industry sector has reduced greenhouse gas emissions by around 30% since 2005, but it needs to accelerate abatements towards 2030 and 2050 while maintaining international competitiveness.[60] No silver bullet exists for industry abatements. Instead, electrification, hydrogen, and biomass as well as CCS are needed, in addition to energy efficiency measures (Figure 30).

RECENT TRENDS AND THE CURRENT STATE

Industrial activity is central to the European economy. In 2021, European manufacturing employed nearly 30 million people and contributed 14.8% of EU GDP.[61] In the wake of the energy crisis and with increased geopolitical tension, industrial competitiveness is currently dominating the political agenda. Europe is increasing its efforts to strengthen its industrial competitiveness, and we see similar trends globally. The US has implemented its Inflation Reduction Act. China has active industrial policies. Japan has developed a Green Transformation Policy, and India has established a Production Linked Incentive Scheme. The commonality across all these efforts is the link between industrial competitiveness and the development of clean and renewable technologies.

Industry sector CO_2 emissions are down 30% since 2005 on energy savings and restructuring.[i,63] Today, the industry sector accounts for 24% of Europe's final energy consumption and 21% of Europe's greenhouse gas emissions.[64] Germany emits 25% of EU industrial emissions. Germany, France, Italy, Poland, and Spain combined are responsible for 60% of industry emissions in the EU.[65]

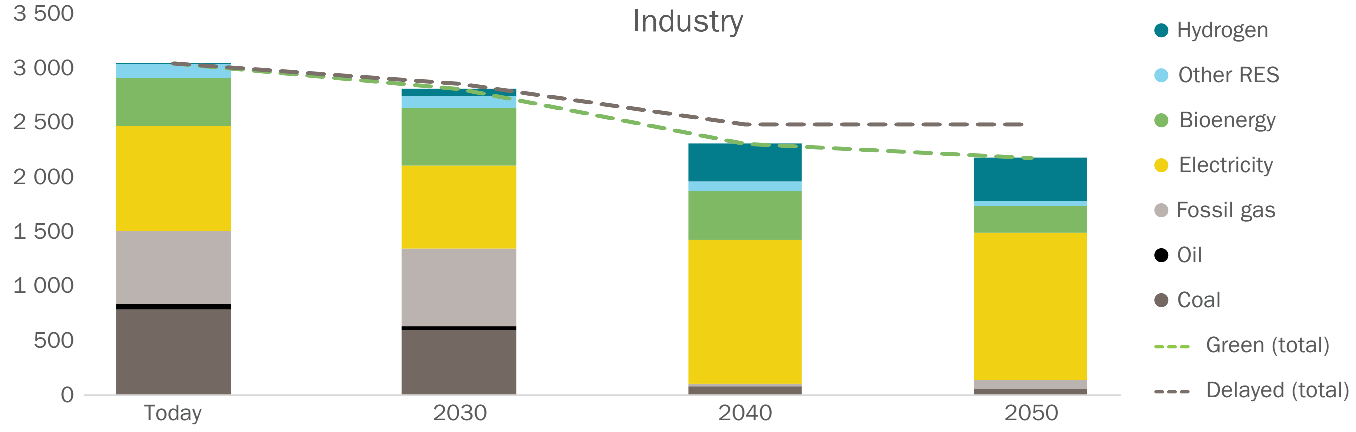
Industry's final energy consumption remained relatively stable in the period following the financial crisis until the pandemic (Figure 31). However, the picture is mixed due to the diversity of the industry sector. While some energy-intensive industries have reduced production, especially after the energy crisis, other sectors such as electronics and machinery have increased (Figure 29).

Despite challenges faced by energy-intensive industries, the overall industry sector has increased value-added[ii], maintained employment levels, and reduced emissions over the past decade (Figure 31). Going forward, the challenge lies in promoting an industrial rebound in a post-energy crisis era while reinforcing climate policies to meet targets.

The pace of recovery for Europe's energy intensive industry hinges on both competitiveness and future demand for energy intensive goods. For segments of the industry sector that produce globally traded goods, the EU's decarbonisation agenda also addresses competitiveness concerns to prevent carbon leakage. Around half of Europe's total industrial energy demand (including feedstock) and 75% of industrial emissions stem from process heating, in the form of steam, hot air and heat in furnaces. Energy carriers used as feedstock in the petrochemical industry account for around 25% of energy use. The remainder is largely for mechanical and other electrical uses.[67]

European industry sectors face varying prospects during their transition. Some industries are already emissions-free or can reduce emissions without major

30 Final energy use in EU industry sector per energy product from today to 2050 in *Green* and total for *Delayed* (TWh).



changes to energy use or business model, such as in parts of food and beverage manufacturing. However, other sectors such as steel and cement must radically transform processes by altering their energy use, using new technology to avoid process emissions, or capturing CO_2. Sectors including battery manufacturing and data centres anticipate growing demand due to energy transition and digitisation trends. Conversely, demand may decrease in sectors such as refineries, due to the global shift away from fossil fuels.

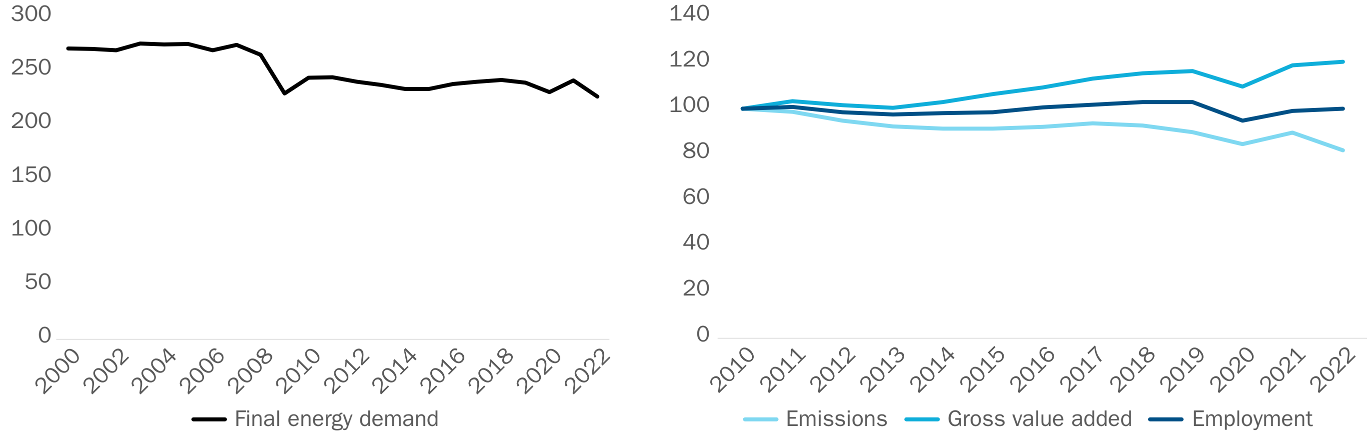
Energy efficiency and circularity will make the transition easier. The EU's steel industry has reduced emissions by 50% per ton of steel produced through process improvements and increased recycling. Similar reductions have been made in the aluminium industry, with some plants achieving a 62% decrease in emissions per ton of aluminium produced. In the steel industry, modern European blast furnaces are approaching the thermodynamic and physical limits.[68]

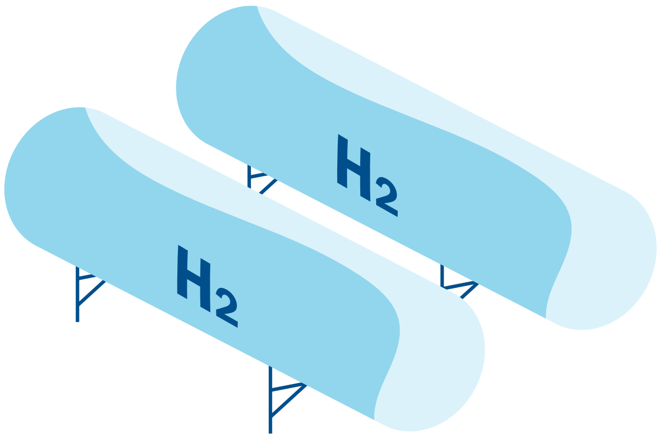
Recycling of materials can reduce energy demand and emissions significantly. Recycled aluminium requires less than 5% of the energy used for primary aluminium, and steel recycling could require up to 10 times less energy than production of primary steel. For recycling, access to scrap is a limiting factor, and at present more than 90% of stainless-steel products are already recycled in Europe.[69]

Optimising material use and substituting with lower carbon alternatives in end-use sectors can help reduce emissions while still providing the same level of service to consumers. For instance, Agora Industries' analysis suggests that optimising material use in the construction sector could reduce EU emissions by 24 million tonnes by 2050.[70]

[i] Industry sector here refers to Manufacturing Industries and Construction including Industrial Processes and Product Use.
[ii] Value-added is defined in Eurostat as the output (at basic prices) minus intermediate consumption (at purchaser prices).

31 Development in final energy demand for the industry sectors in EU27 from 2000 to 2022 (Mtoe, left). Development in greenhouse gas emissions, employment and gross value added for the industry sectors in EU27 from 2010 to 2022, indexed to 2010 (right).[66]





Hydrogen can be used both as process input and to generate high heat, but is less energy efficient than direct electrification.

Electrification from heat pumps or direct electricity use are most efficient when feasible. Electrification is the most important solution for emission reductions in the industry sector. Around 50% of industries' final energy demand comes from process heat, of which fossil fuels account for around 75%. Currently, around half of process heat is used in high-temperature processes (above 500 degrees), while around one-third is used in processes that heat up to 150°C.[71] Industrial heat pumps for lower heat temperatures are already mature solutions. For processes that require heat up to 500 degrees, electric boilers can be an alternative. While there are various solutions for producing high-temperature process heat (above 500 degrees), they face limitations in material applicability and other barriers. Electric arc furnaces are well-established in the steel sector, but their widespread deployment is limited by the availability of scrap steel or direct reduced iron. Ongoing innovation in high-temperature heat pumps is expected to deliver new solutions in the coming years. Particularly interesting are solutions that can both produce and store heat, enabling the use of low-cost renewables like solar and wind power to deliver stable heat for industrial processes.

Bioenergy is important, but sustainable supply is limited. Biomass can be used to generate heat for most processes and can also serve as an alternative to fossil feedstock in several processes. However, supply of sustainable bioenergy is limited, and EU's Renewable Energy Directive sets strict sustainability criteria for the use of bioenergy.[72] Biomass may also contribute to emission reductions in other sectors. The industry sector competes with other 'hard-to-abate' sectors (such as long-haul aviation) for scarce bio-resources. Willingness to pay and the availability of alternative abatement solutions will determine in which subsectors bioenergy will be predominantly used. When combined with CCS, bioenergy has the potential to deliver substantial negative emissions.

Switching to emission-free hydrogen and its derivatives for the chemical industry and high heat processes. Hydrogen offers a decarbonisation alternative for 'hard-to-abate' emissions that are difficult to electrify. Electrification is often the most cost-optimal and energy-efficient decarbonisation route, aided by efficiency upgrades and behavioural changes as outlined in previous sections. Still, for some industrial applications, like chemical processes and primary steel production, emission-free hydrogen is a promising decarbonisation option. Hydrogen can be used both as process input and to generate high heat, though it is less energy-efficient than direct electrification. Today, around eight million tonnes of hydrogen produced from fossil energy are used in the chemical industry and refinery sector.[73] In the steel sector, hydrogen can replace fossil gas in direct reduction of iron, providing a pathway for green primary steel production. Several projects are already in the pipeline, with H2 Green Steel leading the way. They plan to produce five million tonnes of green steel annually in northern Sweden by 2030.[74]

Capturing CO_2 emissions is needed for some sectors. CCS can either remove emissions from use of fossil fuels in process heat or capture process emissions. However, costs remain generally high, and it is difficult to foresee a 100% capture rate. Reaching zero emissions would require CCS to be combined with bio energy or direct air capture. CCS is particularly relevant for newer production facilities to preserve invested capital, for industrial clusters where multiple industries can share infrastructure costs, and in areas with an abundance of

Hydrogen offers a decarbonisation alternative for 'hard-to-abate' emissions that are difficult to electrify.

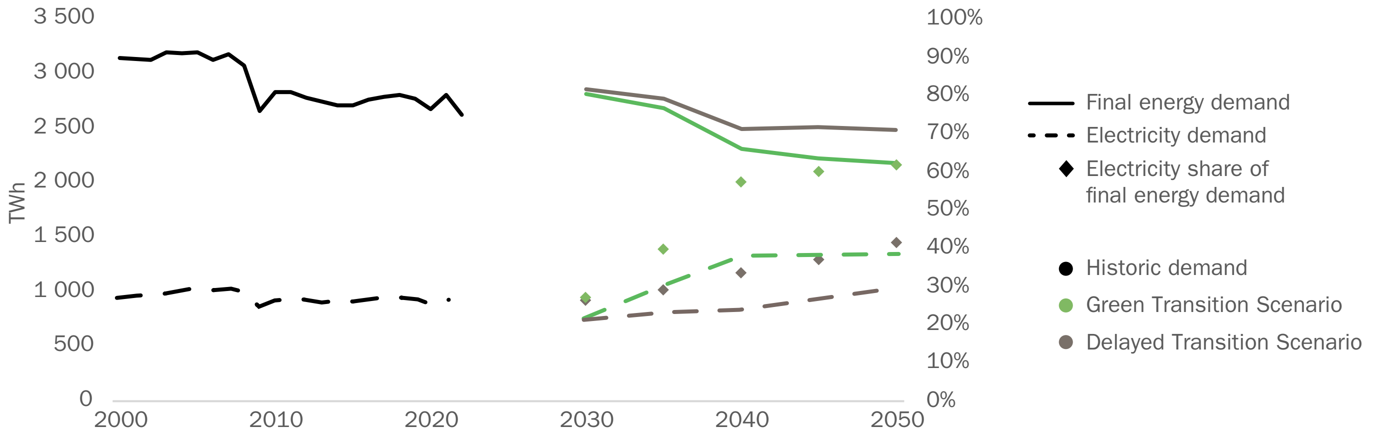
cheap fossil fuels. For certain process-related emissions, CCS is the only viable route and plays a crucial role in reaching a zero-emission society. In the cement industry, where limestone is used for clinker production, few alternatives to CCS exist.

THE INDUSTRY SECTOR IN OUR SCENARIOS TO 2050

In both European scenarios, despite a decline in the total energy intensity of the economy, a relationship between industrial energy demand and GDP growth continues to hold. We project slightly higher demand for all forms of process heat in 2050 in both scenarios. The total growth in energy services from the industry sector is assumed to be below 10%.[i] In the *Delayed* scenario, European GDP growth is slightly lower, leading to reduced energy demand. In the *Green* scenario, a stronger focus on sustainability decreases material consumption, which in turn reduces demand for materials, thereby lowering demand for high-temperature heat.

According to our model scenarios towards 2050, electrification is the most important decarbonisation solution for industry. In the Green Transition Scenario, electricity's share of final industry energy demand more than doubles from 27% in 2030 to 62% in 2050. In absolute terms, it increases from 760 TWh to 1350 TWh. The electrification of industry is primarily driven by strong climate policies and would be significantly delayed with a weaker policy push. Hence, in *Delayed*, industrial electricity consumption is 23% lower (at 1035 TWh) compared to *Green* in 2050 (Figure 32). In the Green Transition Scenario, emissions from low process heat are rapidly reduced, falling by 65% by 2035 and reaching close to zero by 2040. Achieving this primarily involves the use of heat pumps, electric boilers, and bioenergy. Low process heat is used across various industries, with the food and beverages sector accounting

32 Final energy and electricity demand in Industry historic and to 2050 for the Green and Delayed Transition Scenarios (line, TWh) and share of electricity in total final energy (dots, %).



for highest usage. The rapid decarbonisation of energy use in this sector is crucial to meet EU climate targets. However, in sectors such as iron and steel, cement, and high process heat, decarbonisation is expected to be more challenging, with solutions like hydrogen and CCS taking a prominent role as early as 2040 in the *Green* scenario.

In our scenarios, clean hydrogen plays a crucial role in reducing some of the 'hard-to-abate' emissions. In the *Green* scenario, 18% of final energy consumption from the industry is hydrogen by 2050. However, due to its relatively high cost, hydrogen accounts for only 5.5% of final energy consumption in the *Delayed* scenario, due to looser emission constraints allowing for lower cost solutions. The industry sector primarily uses hydrogen to replace existing feedstock (such as grey hydrogen in the chemical industry) and for high-temperature applications. In the *Green* scenario, 38% of hydrogen used in the industry sector (excluding feedstock) serves medium-heat needs. This demand is susceptible to innovations that make direct electrification more practical and cost-effective, such as heat pumps or electric boilers with thermal storage.

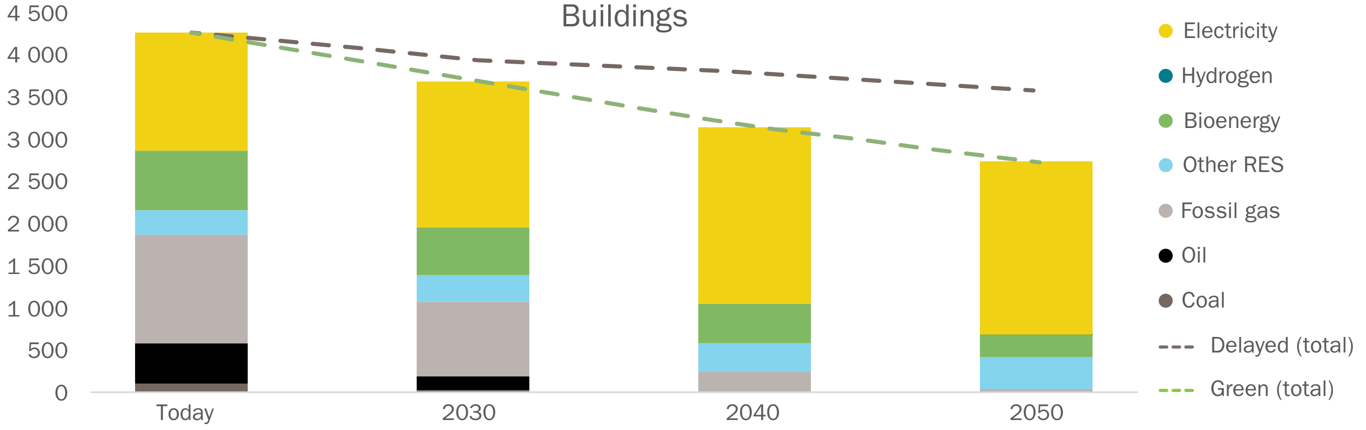
In addition, our model analysis reveals strong competition between hydrogen and bioenergy. A sensitivity analysis with unlimited access to sustainable biomass at current prices shows that hydrogen use in the *Green* scenario is reduced by 58%.

The use of CCS increases substantially towards 2040 in the Green Transition Scenario. The role of CCS is especially prominent in a modelled sensitivity case in which the EU misses the 2030 targets, followed by a massive strengthening of policies towards 2040 and 2050. This illustrates that delaying emission reductions towards 2030 increases the need for more costly solutions by 2040. In the *Delayed* scenario, CCS sees minimal use in the industry sector until 2050. CCS plays the most prominent role in the cement sector. In total, we forecast that 76 million tonnes of emissions are captured in the industry sector in 2040 in the *Green* scenario, of which 36% is from cement production.

For Europe to meet its proposed climate target of 90% by 2040, industry must drastically reduce its emissions. In the Green Transition Scenario, industry is nearly reaching net-zero by 2040 with the help of industrial carbon removal from the use of CCS on biomass, for example in the cement sector. Also, the Blast Furnace-Basic Oxygen Furnaces used in steel making are nearly phased out and replaced with electric arc furnaces and direct reduction. For other industries, the transition will present difficult dilemmas regarding the location of new production lines. Many of the most energy intensive sectors are either situated near coal fields or have historically depended on inexpensive gas from Russia. For some of these industries, it may be economical to relocate to areas offering better renewable resources, as we see with the new steel plants in Northern Sweden. Many of the required investments are capital-intensive and involve long lead times. In energy and industry terms, 2040 is essentially 'tomorrow'. For the proposed 2040 target to be achievable, strong policy incentive must be put in place shortly. Such a prompt transition will have not only economic and environmental, but also social consequences.[75]

[i] Energy services are defined as tasks performed using energy (with the purpose to satisfy an energy demand or need).

33 Final energy use in EU building sector per energy product from today to 2050 in *Green* and *Delayed* scenarios (TWh).



The building sector: Electric heat pumps and renovation are key solutions

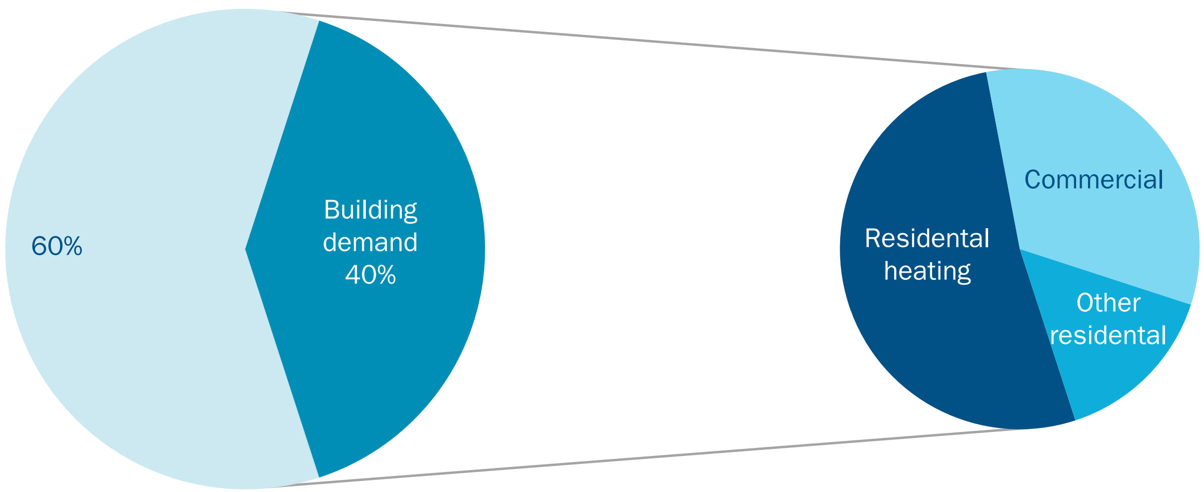
The building sector is the EU's largest consumer of final energy, with over 50% of that demand currently met by fossil fuels. Electrification through heat pumps, improved insulation, and bioenergy are the primary climate-friendly alternatives (Figure 33). In our scenarios, the number of heat pumps increases five to seven times by 2050, as they are economically viable, efficient and cut emissions.

RECENT TRENDS AND CURRENT STATE

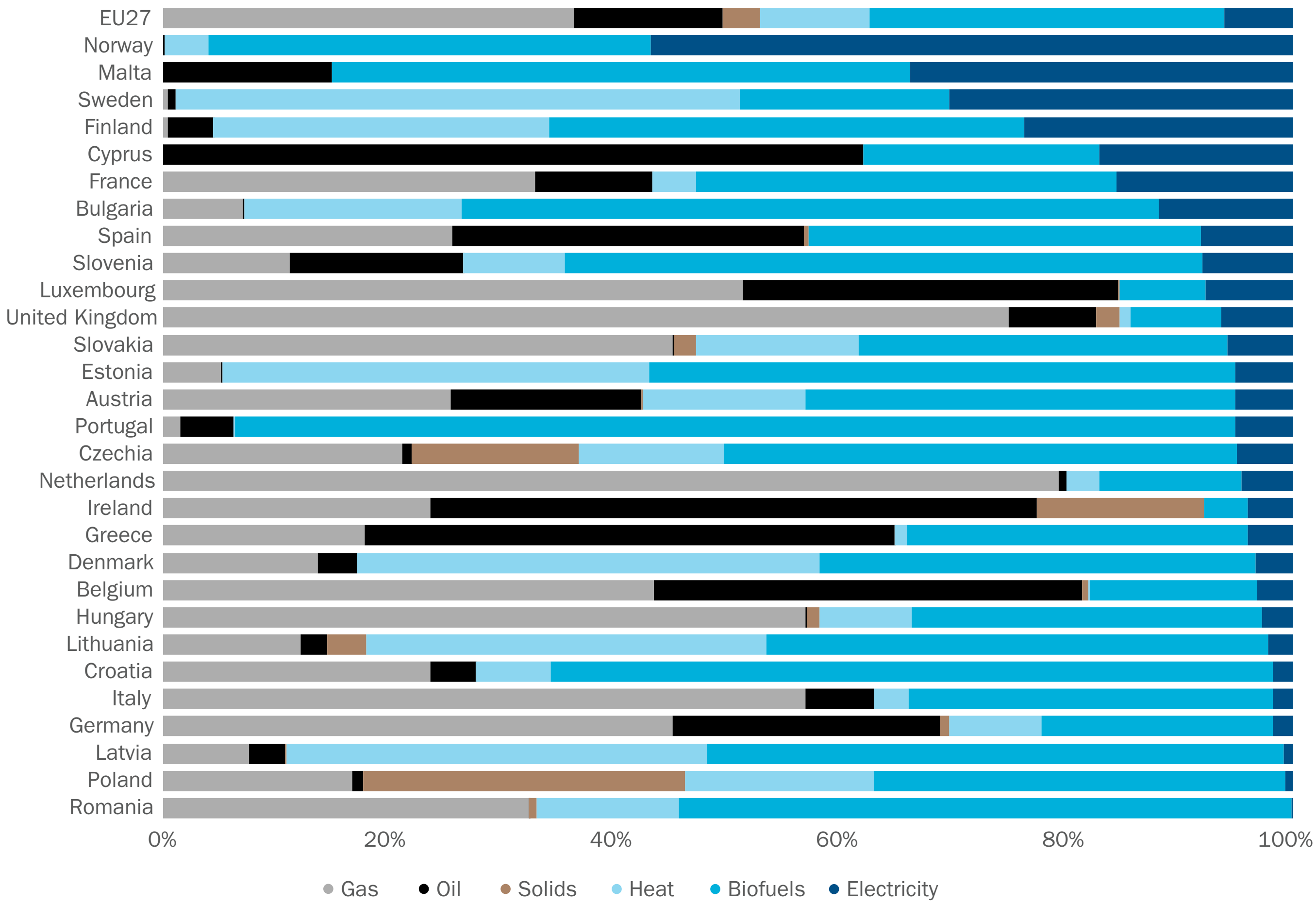
In the European building sector, emissions include direct emissions from burning fossil fuels and indirect emissions from electricity use. Direct building emissions accounted for approximately 13% of the EU's energy-related emissions in 2022, most of which is generated from heating.[76]

Nearly 40% of EU final energy demand is consumed in the building sector, where residential water and space heating accounts for 52% (Figure 34). Direct emissions from buildings have decreased by 36% from 1990 to 2022, despite a nearly 9% increase in final energy consumption during the same period. Since 2010, energy

34 Share of final energy use in EU from building sector and its sub-sectors today (%, 2022).[77]



35 Energy mix in residential heating in Europe today per country (%).[80]



consumption in buildings has trended downward, with a nearly 15% reduction in final energy demand. Improved energy efficiency and increased use of heat pumps have driven these reductions, resulting in a reduction of emissions by more than 30% over this period.[78]

Over 50% of residential heating still depends on fossil fuels, with electricity making up less than 10% and approximately 30% relying on bioenergy. The heating fuel mix varies significantly across countries, highlighting the need for region-specific solutions to effectively decarbonise the building sector and encourage behavioural changes. Fossil gas dominates heating in many European countries, serving over 70% of residential heating needs in the UK and the Netherlands. Only France, Norway, Sweden, and Finland have electricity shares in heating that exceed 10%. Poland stands out with nearly 30% of its heating still reliant on coal, while Spain and Belgium continue to have high oil usage, ranging from 30% to 40% (Figure 35).[79]

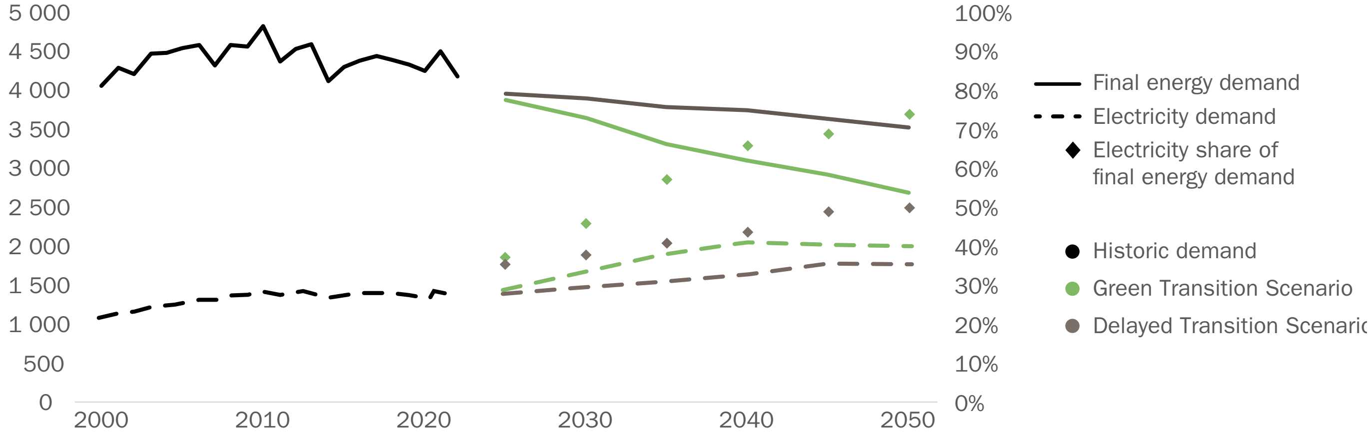
The varying fuel mixes across Europe are also reflected in the CO_2 emissions from the building sector. Germany, France, and Italy emit nearly 60% of total EU direct emissions in the residential sector. If Poland, Spain, the Netherlands and Belgium are included, the percentage increases to more than 80%.[81] Achieving near-zero emissions in buildings requires significant and rapid changes in these countries.

THE KEY DECARBONISATION SOLUTIONS IN BUILDINGS ARE MATURE, EFFICIENT, AND READY, BUT OBSTACLES REMAIN

The fastest and most energy efficient way to reduce emissions in buildings is through direct electricity and heat pumps. In parallel, renovation and behavioural changes to how and when to use energy will be important.

Refurbish and rehabilitate the building stock. The average age of existing buildings and the share of new construction serve as indicators of the overall energy efficiency of the building stock. In Europe, most buildings were constructed before 1990, making large-scale refurbishments necessary to achieve sufficient energy standards and reduce energy demand. The recently revised Energy Performance of Buildings Directive (EPBD) aims to reduce average primary energy demand in residential buildings by 16% by 2030 and 20-22% by 2035. Member States have flexibility in selecting buildings and implementing measures to meet energy reduction goals. However, in countries such as Italy, where over 60% of buildings predate 1990, there are significant hurdles to the deep renovation of them. Nonetheless, to achieve a fully decarbonised building stock by 2050, renovation efforts across all countries must align with the EPBD targets.[82]

36 Final energy and electricity demand in Buildings historic and to 2050 for the *Green* and *Delayed* scenarios (line, TWh) and share of electricity in total final energy (dots, %).[85]



Replace fossil fuels with clean electricity. The EU has set ambitious goals for phasing out fossil heating as part of the updated EPBD. Under this Directive, all new buildings are required to meet a zero-emission standard by 2030, with new public buildings achieving this by 2028. While no specific phase-out date for fossil fuels in existing buildings is defined by the EU, member countries must create renovation plans to eliminate fossil fuel boilers by 2040.[83]

Clean electricity, particularly through heat pumps, is the primary solution for replacing fossil fuels in heating. Heat pumps are well-established and energy-efficient technologies. In 2023, Europe had nearly 24 million heat pumps in operation, with annual sales of almost three million. The REPowerEU strategy aims to double the deployment rate of water-based heat pumps in buildings, reaching at least 10 million additional units by 2027 and 30 million by 2030. Although the action plan for achieving these targets is delayed until late-2024, the total stock keeps increasing. While growth in heat pump sales remained steady until through 2022, certain countries experienced a slowdown in 2023, resulting in slightly lower total sales. France has recorded the highest number of heat pump sales in recent years, yet still has only one heat pump installed for every 10 households.[84] Despite the cost efficiency of heat pumps due to lower running costs, the high upfront investment remains a barrier to widespread adoption. Alongside heat pumps, district heating, wood stoves, and direct electricity play essential roles in phasing out fossil fuels for heating buildings.

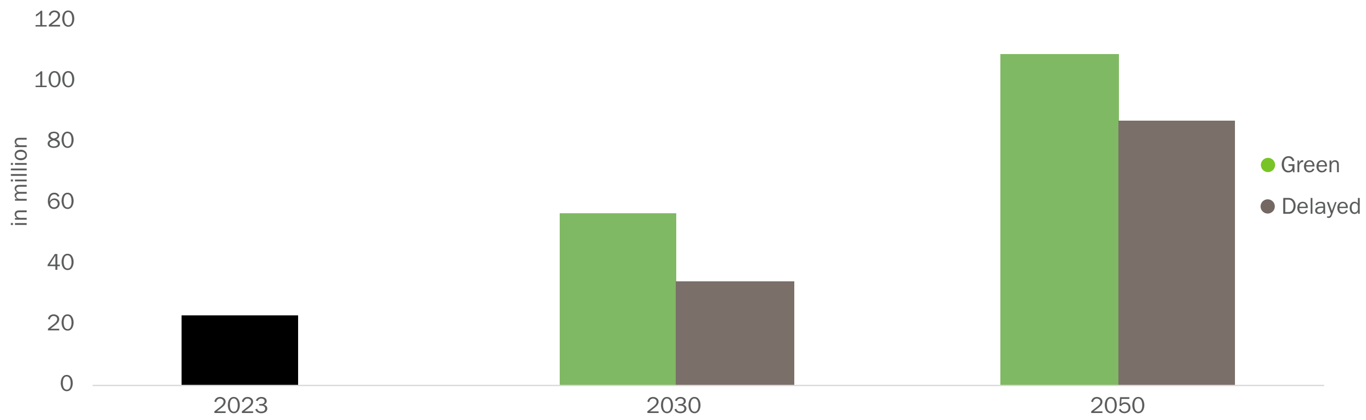
THE BUILDING SECTOR IN OUR SCENARIOS TO 2050

In the Green Transition Scenario, all EU countries prioritise building renovation and upgrades to achieve higher energy standards. Simultaneously, heat pump installations and the phase-out of fossil heating are accelerated. Demand response measures are also implemented, with smart control systems gradually installed in households and public buildings. These efforts enhance energy efficiency and increase flexibility within the sector.

In this scenario, based on the above measures, the EU achieves a nearly 30% reduction in final energy use in its building stock in 2050 compared to 1990 levels (Figure 36). The shift to heat pumps and electricity for heating, combined with rapid rate of renovation, play key roles. Direct electricity use and heat pump adoption cover 75% of the final energy demand in 2050 in this scenario. District heating and bioenergy account for the remaining share, except for a small portion of fossil gas. Already by 2035, oil and coal for heating are completely phased out, while gas consumption is reduced by more than half. The share of fossil energy in final energy drops from around 40% today to below 20% in 2035, and to just 1.5% in 2050. Due to the high efficiency of heat pumps, combined with the growing demand for bio resources in other sectors and the limited sustainable bio resources, the use of bio boilers and wood stoves also declines. Bio energy accounts for only about 10% of final energy demand in buildings by 2050.

In the Delayed Transition Scenario, building renovation progresses more slowly, and the adoption of heat pumps lags. As a result, the energy service increases towards 2050, despite reduced economic growth. The limited energy efficiency gains from renovations and the growing need for cooling contribute to this trend. Although demand for fossil fuels still decreases, it does so at a slower pace than in the *Green* scenario. The relatively higher energy demand, due to slower renovation and energy efficiency measures, poses challenges for the

37 Total heat pump stock in EU27 including UK, Norway and Switzerland, today and in 2030 and 2050 in the *Green* and *Delayed* scenarios.



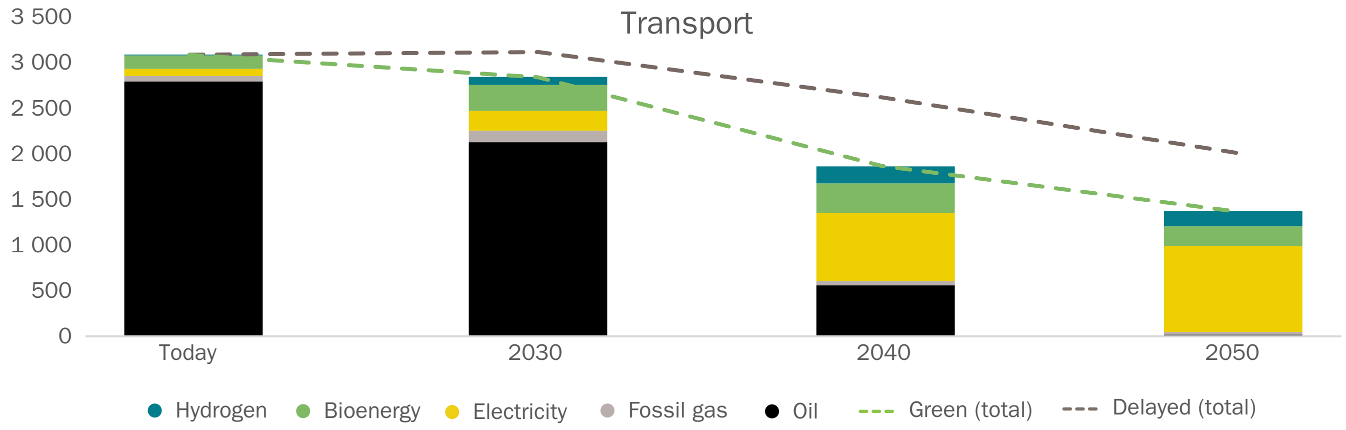
phase-out of fossil fuels. In this scenario, coal and oil are phased out in buildings by 2035, while gas sees a slight increase alongside electricity during this period. However, by 2050, gas consumption is reduced by 40% from today's levels as more heat pumps are deployed. Despite this decline, gas continues to play a substantial role in heating, accounting for just over 20% of final energy demand in 2050.

In the *Delayed* scenario, building emissions decrease by approximately 65% in 2050 compared to 2019. In the *Green* scenario, meanwhile, the buildings sector becomes nearly emission-free by 2050. Notably, achieving this transformation does not require new or immature technologies. The primary difference lies in energy efficiency, driven by increased renovations and the widespread adoption of electric heating and heat pumps.

Location: Heimdal district heating plant, Trøndelag, Norway

Direct electricity use and heat pump adoption cover 75% of the final energy demand in 2050 in the *Green* scenario. District heating and bioenergy account for the remaining share, except for a small portion of fossil gas.

38 Final energy use in EU transport sector per energy product from today to 2050 in *Green* and *Delayed* (TWh).



The transport sector: Electric cars are on the rise, but car turnover rate is slow

A rapid shift to electric passenger cars will cut emissions and energy use in the two scenarios. Passenger cars are responsible for almost 60% of domestic transport emissions in the EU today. Heavy transport faces different challenges, with no single fuel solution. The transition of this segment is slower, and the speed varies across the scenarios. Biofuel serving as a transitional fuel before electricity and hydrogen shares increase (Figure 38).

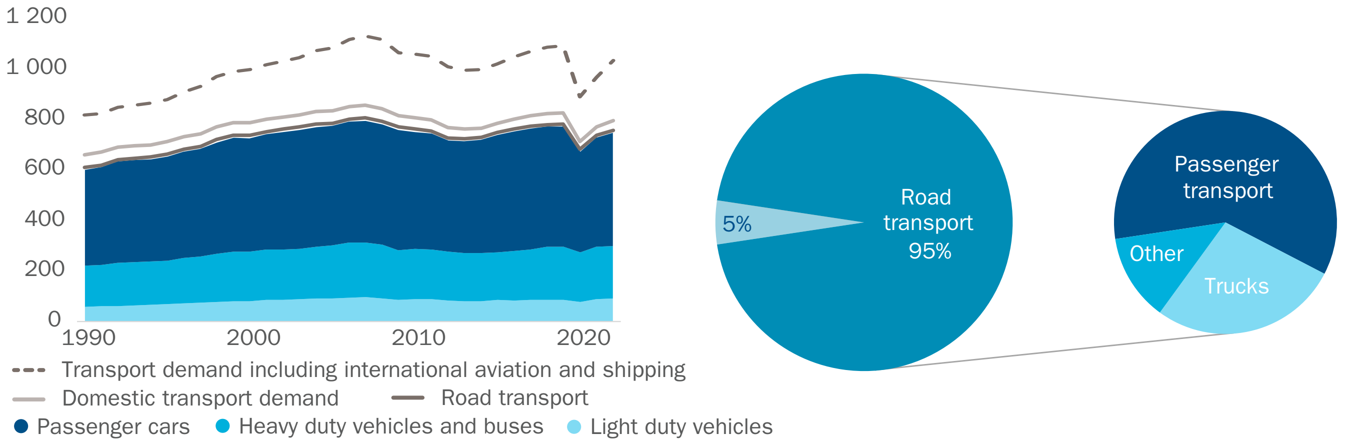
RECENT TRENDS AND CURRENT STATE

In 2022, the transport sector accounted for 30% of the EU's final energy consumption and close to 28% of the EU's energy-related CO_2 emissions. Road transport is responsible for more than 95% of domestic transport emissions and passenger cars contribute close to 60% of road emissions, mainly from liquid fossil fuels (Figure 39). As such, passenger cars are by far the largest contributors to domestic transport emissions in the EU today. Emissions from the EU's transport sector rose until 2007, followed by a decline through 2013, driven by the financial crisis, efficiency improvements, and periods of high oil prices (Figure 39). Since then, transport emissions have increased to close to 2007 levels again, despite a temporary drop during the pandemic (Figure 39).[86]

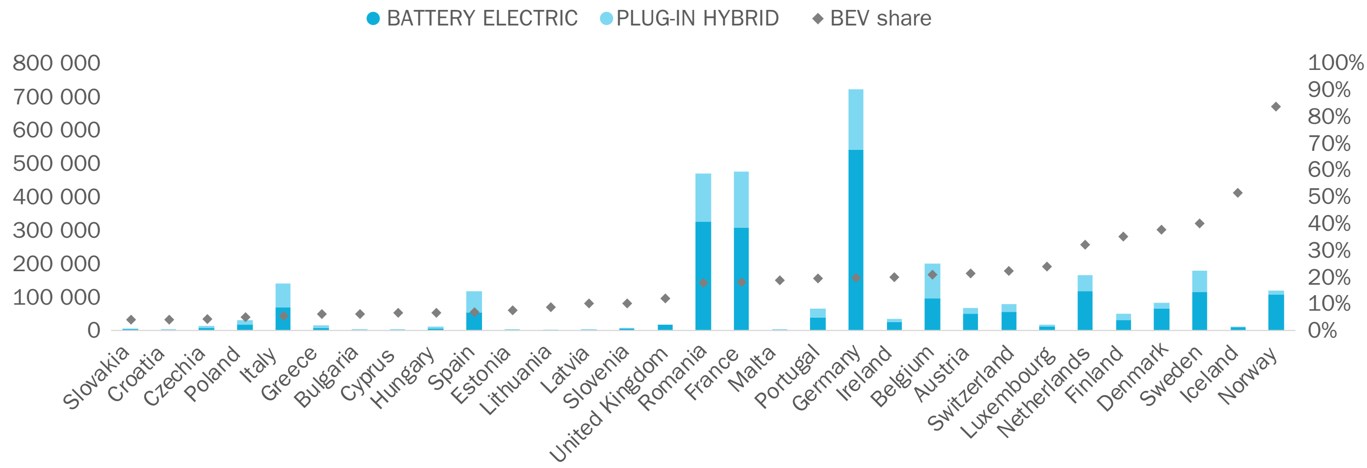
The growth in vehicle stock is a significant factor driving transport emissions. Since 2012, the total passenger car stock in EU and UK has increased by an average of 1.75% per year, adding around 4.5 million cars to the road annually. Despite increasing electric vehicle (EV) sales, fossil fuel cars (including hybrids) still accounted for 75% of new car sales in 2023. The five most populous countries account for 70% of the EU's passenger car fleet and nearly 70% of road transport emissions. Decarbonising the passenger car fleet in these five countries alone could reduce total road transport emissions by 40%. For heavy-duty vehicles, the same five countries have the largest fleets, contributing to 20% of the EU's total road transport emissions.[88]

Norway is the frontrunner in EV sales, with EVs accounting

39 Historic emissions in total and per transport subsegment from 1990 to 2022 (left, Mt CO_2) and share of road transport of total domestic transport emissions in 2022 and its subsegments (right, %).[87]



40 EV sales in total in 2023 including BEV and PHEV (left axis, number) and in share of total car sales (%).[90]



for 90% of annual new passenger car sales. Sweden achieved a 60% EV sales share in 2023, while Denmark and Finland, respectively, reached 46% and 54%. Other European countries have also experienced a rise in EV sales. Belgium and the Netherlands have exceeded a 40% EV sales share, while Germany, France, and the UK saw the highest absolute growth in EV stock, though they maintained around a 25% EV sales share. In contrast, Italy, Spain and many Eastern European countries are trailing, with EV sales shares below 12% (Figure 40).[89]

DECARBONISATION SOLUTIONS ARE DIFFERENT FOR EACH TRANSPORT SEGMENT.

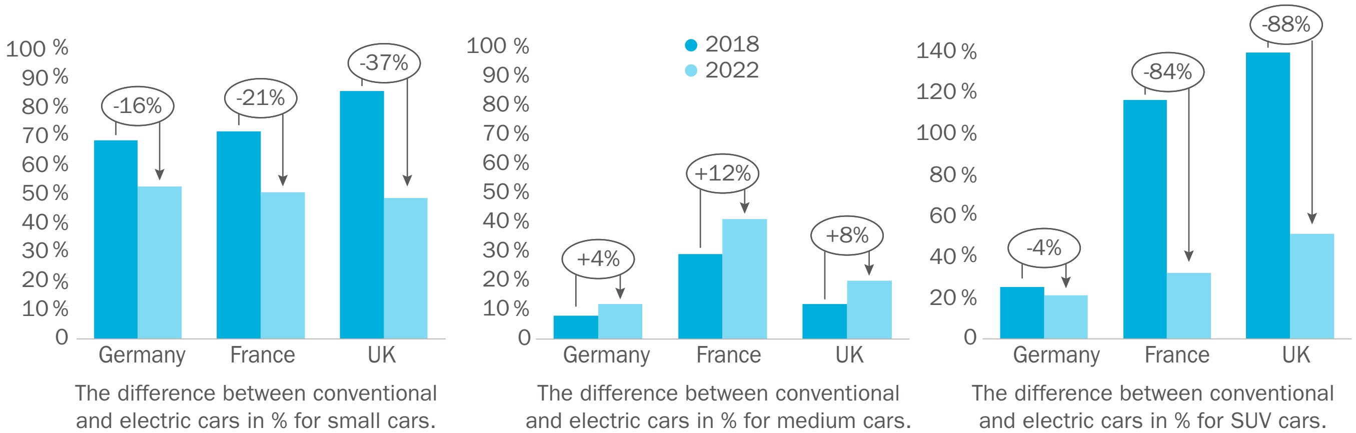
There are currently around 257 million passenger cars on the road in the EU, and of these, more than 90% are fossil fuel powered.[91] Light commercial vehicles contribute an additional 30 million cars.

Due to technology improvements, the retail price (purchase cost) gap between fossil cars and EVs is shrinking (Figure 41). In addition, lower fuel costs over the lifetime of an EV mean that the total costs of ownership of EVs are approaching the same levels as their fossil counterparts.[92]

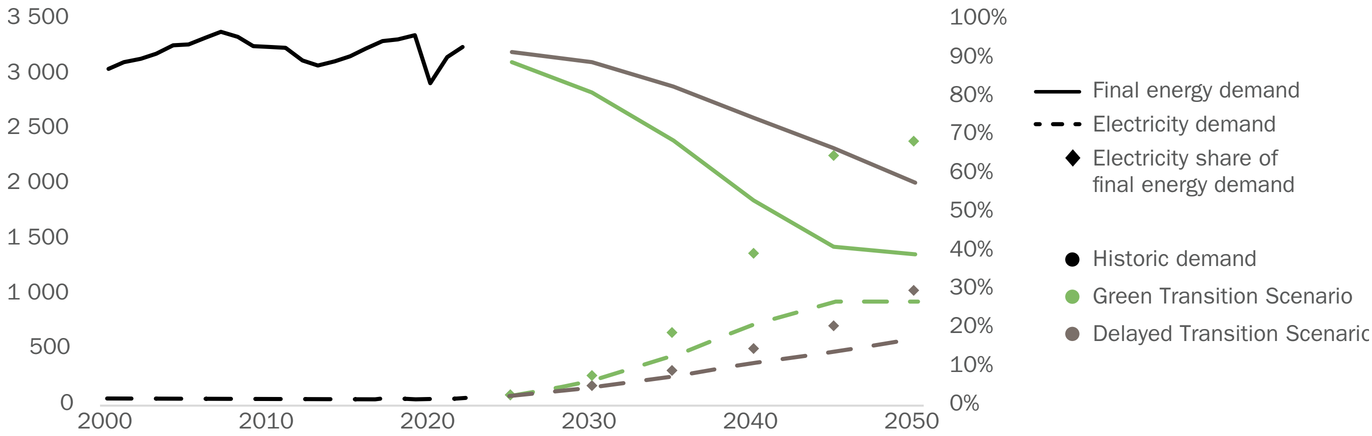
However, replacing the entire European car fleet is a slow process. To meet the goal of replacing all existing fossil fuel cars with zero-emission alternatives by 2050, more than 10 million cars would need to be replaced with battery electric vehicles annually from 2025 onwards. Behavioural shifts, such as increased use of public transport or car sharing, could help reduce the overall car stock. By 2030/2035, when the “early mover” electric cars reach 10 to 15 years of age, annual new car sales in the EU will need to rise to at least 20 million on average to also replace decommissioned (or exported) used electric cars. The transition to fully electrified passenger and light commercial vehicle segments is feasible if the EU achieves a 100% sales share of electric vehicles by 2030 at the latest. However, if fossil fuel vehicle sales remain significant through 2035 and 2040, reaching zero emissions in light-duty transport by 2050 will become increasingly challenging.

Charging infrastructure is crucial for electrifying transport. The EU estimates a need for 3.5 million public chargers by 2030. As of 2023, only 18% of the target has been reached. This means that nearly three million chargers must be installed by 2030. Currently, 61% of EU public chargers are in Germany, France, and the Netherlands,

41 Retail price (purchase cost) gap between fossil and electric vehicles 2018 and 2022, for small, medium and large (SUV) cars from left to right.[93]



42 Final energy and electricity demand in Transport historic and to 2050 for *Green* and *Delayed* scenarios (line, TWh) and share of electricity in total final energy (dots, %).



while the other 24 countries share the remaining 39%.[94] Accelerated charger expansion in Spain, Italy, and Poland is particularly vital for decarbonising road transport.

Heavy-duty road transport faces different challenges, with no single fuel solution. To fully decarbonise heavy duty transport by 2050, the EU would need 250,000 to 300,000 new emission-free trucks annually from 2025 onwards. While there is progress toward zero-emission trucks, infrastructure remains key to build momentum. Access to public chargers is crucial for heavy-duty electric vehicles, particularly for super-fast charging along highways. A mix of battery-electric, biofuel, hydrogen and e-fuel trucks are likely to be essential solutions for long-haul routes. Sustainable biofuels can blend into existing fuels, while hydrogen fuel cell vehicles rely on new refuelling infrastructure. Hydrogen offers zero or close to zero emissions from well to wheel if produced through electrolysis from renewable power or from fossil gas with CCS, provided minimal leakages of hydrogen. The EU aims to build hydrogen stations in 424 cities and every 200 km along TEN-T road networks by 2031. However, as of August 2024, only 166 such stations exist in EU.[95] Accelerating the rollout of hydrogen refuelling stations is essential for encouraging trucking companies to invest in hydrogen-powered trucks.

Aviation and shipping emissions pose challenges for decarbonisation. Electricity is not a straightforward solution for a large share of these segments today, so they rely more on other low-carbon or zero-emission alternatives in addition to efficiency improvements. In the EU, domestic aviation and shipping contribute a relatively small share of energy-related emissions compared to road transport. Domestic aviation accounts for 1.6% of EU's transport CO_2 emissions, while shipping contributes 2.2%. These figures exclude emissions from international bunkering, which further adds to the total.[i,96]

THE TRANSPORT SECTOR IN OUR SCENARIOS TO 2050

In the Green Transition Scenario, transport is still a few years behind buildings in the shift towards clean energy and emission reductions. Both light commercial vehicles and passenger cars undergo a significant shift towards electric vehicles, and by 2050, these segments are nearly 100% electric in this scenario. The improved efficiency of electric vehicles compared to fossil fuel vehicles leads to more than a 60% reduction in final energy demand for road transport.

For trucks, the transition to emission-free alternatives is slower. Biofuels serve as a transition fuel, increasing in use until around 2045, before gradually decreasing as electricity and hydrogen to some degree take over. Biomass availability is limited, which means that by 2050, more biofuel is allocated to aviation, which has fewer alternatives. Even in the Green Transition Scenario, long-distance trucks still have some diesel-fuelled vehicles on the road in 2050, but over 50% of the final energy demand for trucks is met by electricity, primarily for short and medium distances. Additionally, nearly 20% of truck energy demand is fuelled by hydrogen.

Beyond the shift to electricity, car sharing is on the rise, and autonomous vehicles are maturing in the Green Scenario. For passenger vehicles, car sharing reduces the required car stock, and the total fleet growth flattens and begins to decline towards 2050, whereas the average kilometres per vehicle rises. For trucks, increased deployment of autonomous vehicles reduces the energy use and the total number of trucks needed. Domestic aviation and maritime must also decarbonise substantially towards 2050. In the *Green* Scenario, the EU's domestic aviation sector becomes highly reliant on biofuel, gradually increasing its share of biofuels in final energy to nearly 20% by 2035. Due to strong policy support in this scenario, the use of biofuel, synthetic fuel, and hydrogen surpasses the current 2050 SAF targets for aviation as early as 2040, leading to the phase-out of oil use before 2050. In the EU's maritime sector, approximately 8% of final energy is still fossil gas in 2050, with oil being phased out by 2050. Electricity is used for ferries and shorter distance vessels, including the energy used in ports. Electricity use in maritime accounts for around 8% of final energy in 2030, increasing to 25% by 2050. Hydrogen and ammonia account for over 50% of domestic shipping demand in 2050. In total, transport reaches nearly 70% electrification of final demand in 2050 according to the Green Transition Scenario – this is a significant jump from 8% in 2030 (Figure 42). Combined with biofuel and other renewable fuels, the transport sector approaches near-zero emissions by 2050.[ii]

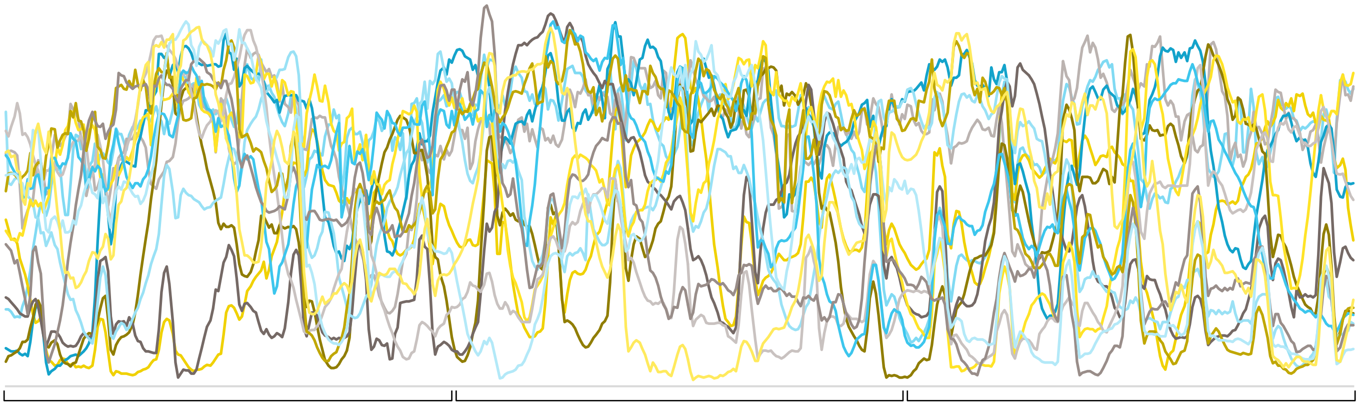
In the Delayed Transition Scenario, the transport sector faces major hurdles in the shift to a decarbonised sector as the incentives to switch to electric cars are reduced due to other priorities and less effective policies. With lower sales and slower turnover of the car fleet, the transition is far slower. In this scenario, the current commitment to ban fossil cars in new sales from 2035 is postponed as priorities change. Despite delays, progress is made in electrification of the passenger vehicle segment. In 2030, the number of electric cars on the road quadruples compared to 2025, covering 7% of final energy in passenger cars. In 2050, electricity accounts for over 50% of final energy demand in passenger cars. When combined with a 15% biofuel share, emissions in the road segment decline by more than 70% compared to current levels.

As infrastructure for both fast charging and hydrogen refuelling stations along important highways are de-prioritised across the EU, and policy priorities are shifted, the truck segment relies on diesel fuel for a longer period in the *Delayed* scenario. Biofuel blend-in is gradually increasing and reduces some emissions for long-haul transport. Electricity and hydrogen only cover 14% of final energy demand in the heavy road segment in 2050, as investment costs remain higher than conventional trucks and infrastructure is lagging. For the total transport sector, emissions in 2050 are still reduced by 70% compared to 2022 levels, mainly due to passenger transport. More biofuels are used to decarbonise the transport sector in the *Delayed* scenario compared to the *Green* scenario, as electrification increases at a slower pace. Compared to current levels, the use of biofuel in road transport is reduced in the *Green* scenario and increases 2.5 times in the *Delayed* scenario.

[i] If international bunkering was included, aviation and shipping would account for 23% of EU's total transport emissions (including international).
[ii] International bunkering is not included.

The efficiency of electric vehicles compared to fossil fuel vehicles contributes to a 60% reduction in final energy demand in these segments.

43 Hourly generation from solar PV and wind power together for 14 weather years during the first three weeks in 2040, illustrating the weather dependent variation in production (TWh).



Solving the flexibility challenge

A mix of clean flexibility solutions are available today and need to scale up to handle the fast ramp-up of wind and solar power generation in the European energy systems. In a German case analysis, system batteries and interconnectors are the largest contributors to flexible capacity in 2050, followed by demand response and clean gas peakers. The flexibility challenge is manageable and must be solved by multiple sources and solutions.

For a smooth, secure and cost-effective energy transition, growth of intermittent renewable power must be complemented by a parallel ramp-up of flexible energy solutions. In both our scenarios, solar and wind power capacity in the EU increase by four- and six-fold from current levels to 2050, replacing fossil generation and facilitating electrification. New adequate flexibility solutions must be deployed to handle the increased variability in power generation.

The need to add more flexible solutions, including demand response and high connectivity are increasingly visible. In 2023, there was a surge in negative power prices, driven by the rapid expansion of renewable capacity and limited grid connections, with occurrences increasing more than ten-fold from the 560 recorded the previous year. In 2023, Germany experienced 300 hours of negative power prices and became a net importer of electricity as more nuclear capacity was phased out.[i] Meanwhile, day-ahead power prices in Europe exceeded the cost of operating a gas power plant on more than 100 days in 2023.[97] This showcases that despite their relatively low utilisation, gas power plants continue to play a central role in providing flexibility.

Several climate-friendly flexibility solutions currently exist, and a mix of different solutions will be required to secure a robust power system in the future. A cost-optimal transition involves flexibility provisions from a variety of sources, spanning different timeframes and regions, facilitated by grids and interconnectors. Key solutions include hydropower with reservoirs, pumped-hydro, battery storage, smart EV charging, flexible electrolysers, other demand side response measures, and grids. Less mature technologies are also emerging, including several long-duration storage solutions (such as for the storage of hydrogen to produce electricity during peak hours). To unlock the full potential of flexibility, it is crucial that market price signals are reaching the flexibility providers, and that an appropriate policy framework facilitates a cost-efficient build out of these different flexibility solutions. Flexibility is needed to solve everything from fluctuations ranging from seconds and minutes to seasonal variations spanning months and years. This creates a significant coordination challenge that is expected to be solved in the Green Transition Scenario, while lagging in the *Delayed* scenario.

A German case – illustrating flexibility needs and solutions

To shed light on future flexibility needs and to quantify how the electricity system may adapt to a more weather-driven supply side, we have simulated European power market balances at hourly granularity, based on observed weather for 14 historical weather years, between 2005 and 2018.[ii] We have analysed the German power market in 2030, 2040, and 2050 to illustrate the evolving flexibility needs and how they can be met, using a detailed

Examples of solutions are hydropower with reservoirs and pumped-hydro, battery storage, smart EV charging, flexible electrolysers, other demand side response and interconnectors.

Location: Alta hydropower plant, Troms and Finnmark, Norway

power simulation model with hourly resolution. As the largest greenhouse gas emitter in the EU and with the biggest power sector (with approximately 240 GW of installed capacity and 500 TWh of generation today), Germany serves as a key example. The German power sector has already started its massive transition with the phase-out of coal and nuclear. Power sector emissions have declined significantly from 2000, as the share of coal generation in the power mix declined from more than 50% in 2000 to 27% in 2023. Meanwhile, wind and solar power increased, reaching (at present) a 39% share of total generation. Overall, German greenhouse gas emissions have decreased by approximately 46% since 1990.[98]

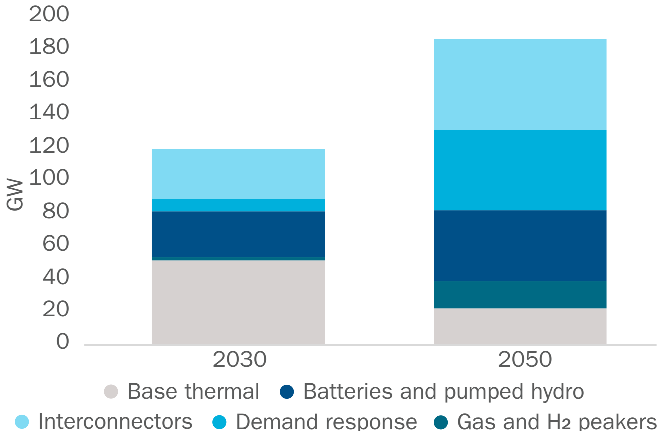
Figure 43 illustrates the large variation in hourly generation from intermittent sources, for three selected winter weeks in Germany in 2040. In our analysis, the average annual solar and wind shares reach 21% and 52%, respectively, in 2040 across the 14 weather years, compared to approximately 12% and 23% today. Thermal power plants are reduced to an average 13% share, compared to more than 40% in 2023.[99] As can be observed during this selected period, there are significant variations in solar and wind power generation between hours, days, and weather years which must be balanced by a mix of flexibility solutions. Typically, wind power generation contributes particularly to increased variability across weeks and seasons, whereas solar PV predominantly impacts the daily pattern.

In the model analysis, the change in generation mix leads to a doubling of flexibility solution capacity over the period (GW). In this case study, system batteries and interconnectors in Germany are the largest contributors to flexible capacity, accounting for more than half by 2050. Demand side response, including smart EV chargers, smart heating and smart electrolysers, provides about one quarter, while clean gas peakers, powered by hydrogen or fossil gas with CCS in 2050, supply roughly 10%. The remaining 10% comes from other thermal sources, such as combined heat and power plants (CHP) which gradually become cleaner. This represents a significant shift from today, where 60% of the flexible capacity stems from thermal power plants (Figure 44).

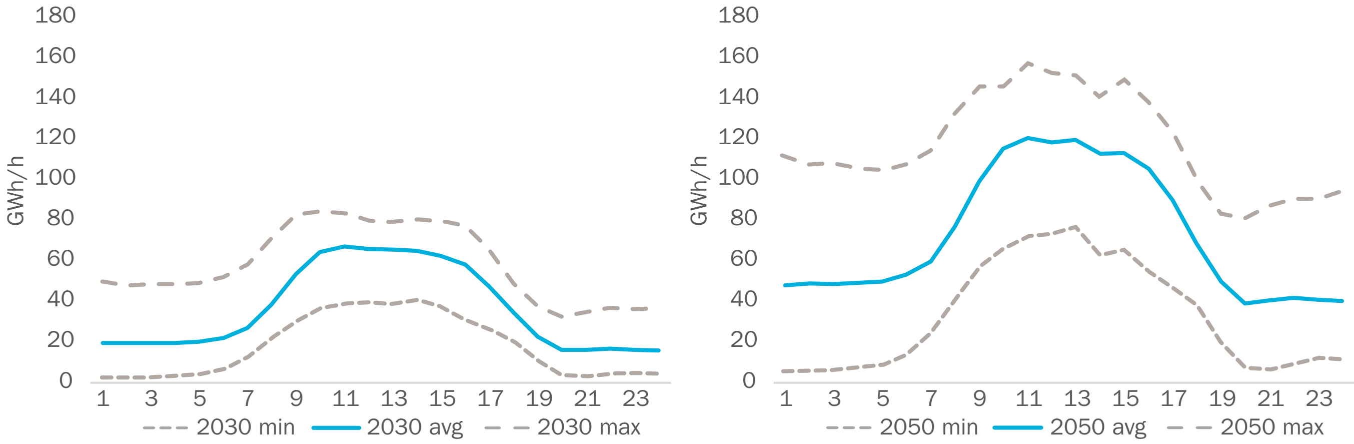
[i] The occurrence of negative prices in 2023 are a consequence of the installation of large numbers of renewable generation capacity in many countries that do not react to market prices, either for technical reasons (for example smart metering and control systems are not installed), or due to incentives such the Renewable Energy Source Act (EEG) in Germany. Towards 2030 and 2050, it is expected that solar and wind power plants will be exposed to and be able to react to the power market price fluctuations, while in parallel smart demand, batteries and other flexible solutions are incentivised and able to utilise periods of low power prices to a much larger degree than today.

[ii] A weather year is a consistent set of parameters (wind speed, precipitation, temperature, solar radiation) from a historic year resulting in hourly electricity consumption and renewable electricity production patterns.

44 German capacity of flexibility in 2030 and 2050 in our analysis (GW).



45 German solar and wind power generation during 24 hours in 2030 (left) and 2050 (right) (TWh).



INTRADAY VARIATIONS

Solar PV generation is the main contributing factor for increased flexibility needs during the day (Figure 45). Intermittent renewable energy generation peaks mid-day and is lower in the evenings, early mornings, and night, as solar PV output follows the sun's cycle. This pattern is changing towards 2050 due to increased intermittent generation overall and due to the higher share of wind in the power mix that provides power during nights (Figure 45).

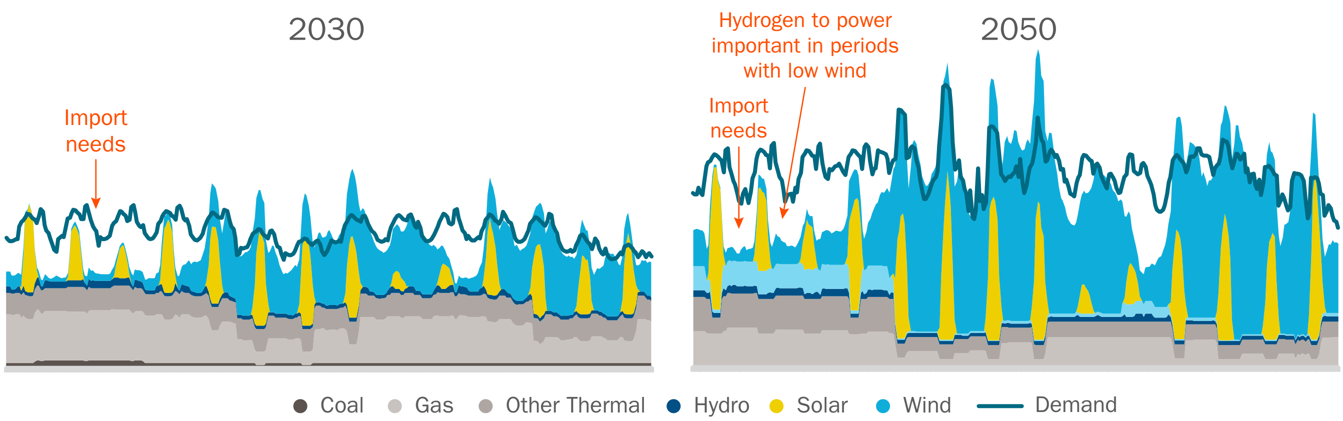
In Germany, solar and wind power generation partially complement each other, making it logical to analyse these technologies together.

VARIATIONS WITHIN WEEKS

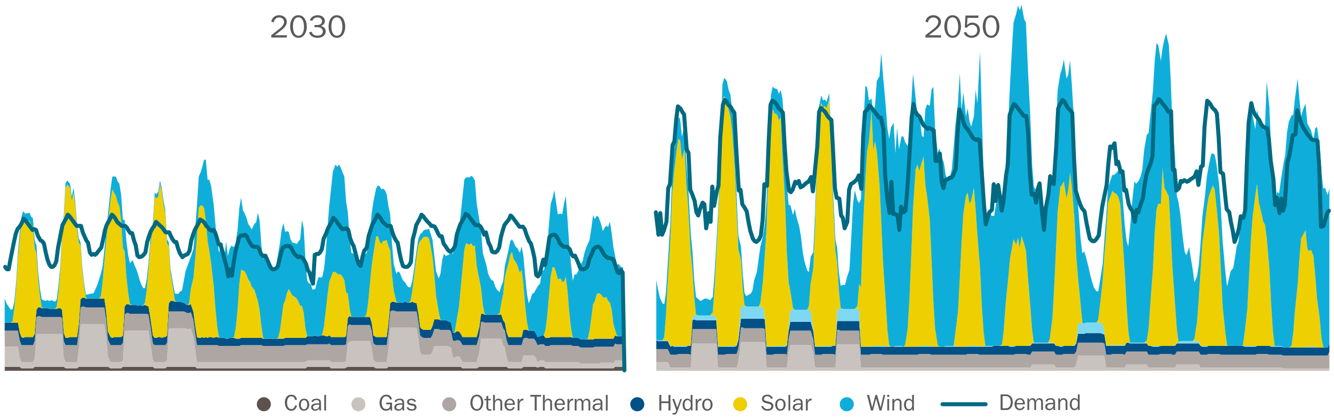
To illustrate how the electricity system may adapt to a more weather-driven supply side over weeks, we have selected two typical winter weeks and two typical summer weeks in Germany, for 2030 and 2050 across the same 14 weather years, with hourly resolution (Figures 46 and 47). In this timeframe, the variability of wind generation becomes more apparent.

Typical winter weeks in Germany are characterised by relatively low solar and hydropower generation and high demand. At times when wind generation is also low, the electricity system faces balancing challenges. Flexible providers – such as gas peakers, batteries, other storage solutions, interconnectors, and demand side management (DSM) – will need to step in during periods of market tightness to fill the supply gap. The need for flexibility is even higher in 2050, compared to 2030, as the share of the intermittent generation and total electricity demand increase significantly. By 2050, clean hydrogen will join gas peakers, interconnectors, and DSM, which already play an important role in 2030, in addressing tight market periods. In our model analysis, green hydrogen is produced during low-price hours with high renewable generation and used in gas-engines to generate electricity during high-price periods with limited renewable output towards 2050. This requires the development of large hydrogen storage facilities in Northwestern Europe.

46 Winter: German electricity generation, week four and five, weather patten 2017 (TWh, 2030, 2050).



47 Summer: Germany electricity generation, week 25-26, weather patten 2017 (TWh, 2030, 2050).



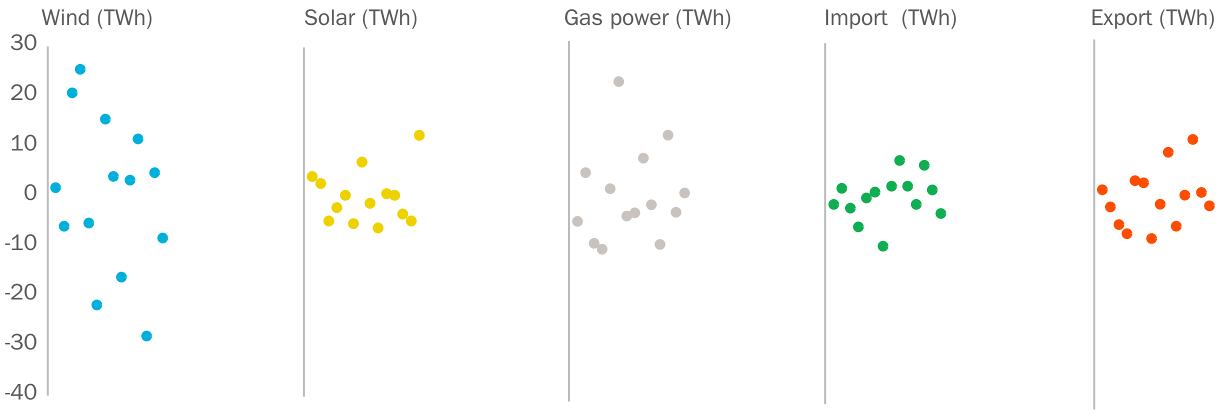
During typical summer weeks, generation is dominated by high solar, hydropower, and wind generation in Germany while peak demand is usually relatively low. Southern Europe differs during this period, as cooling drives higher electricity consumption during daytime. For hours when renewable generation exceeds domestic demand, energy storage, demand response, and export can help the system absorb generation to avoid curtailment of solar and wind. In our analysis, short-term flexibility needs are primarily met by standalone batteries that have become far cheaper over the last decade. In addition, smart EV charging and other demand response, including flexible operation of electrolysers, may significantly contribute by 2050. To achieve this, consumers must be exposed to the right market signals and be given the right instruments. Then, smart demand response can help reduce consumer's energy costs while helping to balance the system. Without sufficient flexibility resources or interconnections built in parallel with more intermittent renewables, there may be periods of curtailment for surplus solar PV or wind generation, followed by periods of very high prices.

INTERANNUAL VARIATIONS

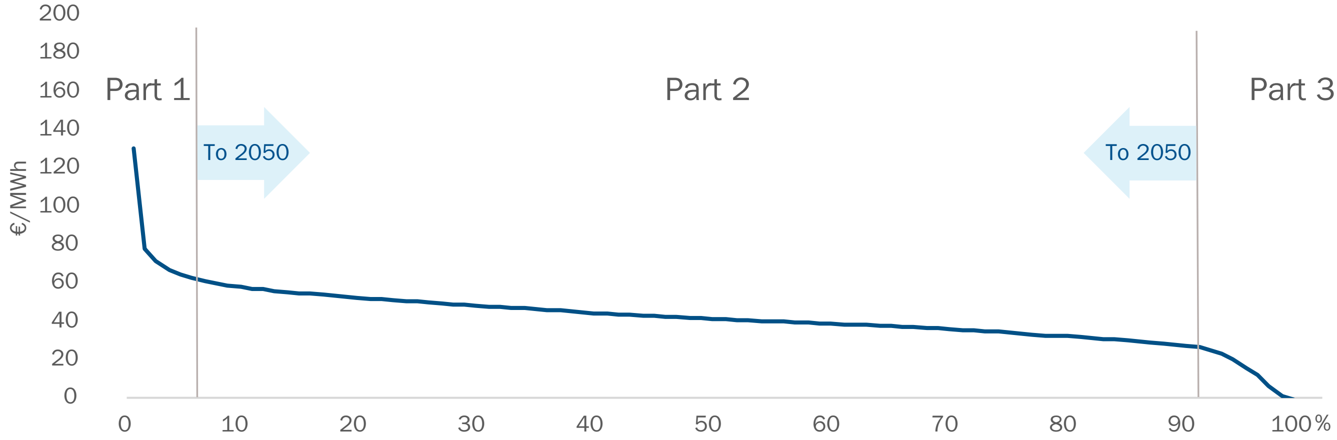
Variations in weather and climate between years has an increasing impact on Europe's energy systems. Using the same 14 weather years, as previously described, the figure below illustrates the interannual weather-driven variability in wind and solar power supply, along with the corresponding variation in gas power generation, imports, and exports for Germany in 2040 (Figure 48).

The analysis shows that wind power has the largest year-to-year variability (Figure 48). Wind power's interannual variability stems from weather variations, and our analysis shows that gas power is a main provider of interannual, seasonal flexibility. Annual gas power generation varies by more than 20 TWh higher and 11 TWh lower than average hourly production of around 90 TWh in 2040. This corresponds to 25% and 12% deviations from average, respectively. There is also significant variability in export and import between Germany and its neighbouring countries over the 14 weather years, illustrating how interconnectors also contribute to interannual flexibility (Figure 48).

48 Difference in average annual output (generation, demand and export and import) in TWh in 2040, each dot representing one of the 14 weather years (x-axis).



49 Price duration curve in Germany in 2019.



Future variations in prices

As the share of intermittent renewable generation surpasses 80% in Germany and new flexibility resources are introduced on the supply and demand sides, the variability of wholesale power prices and the shape of the price duration curve undergo significant changes.[i]

Flexibility solutions soften price spikes in periods of low renewable generation and high demand, while supporting prices during periods of high renewable generation, therefore reducing the need for curtailment. The price duration curve can roughly be divided into three parts (Figure 49).

Part 1. **The steep upper part of the price duration curve represents periods of high demand and low renewable generation.** This period has a longer duration in 2050, compared to today, but also broader range of outcomes between weather years. In our analyses for this part of the curve, the marginal provider in a decarbonised power system will typically be hydrogen gas-peakers or demand response from industrial plants that are compensated for stopping production when there is high stress in the system.

Part 2. **The middle part of the curve, representing periods of average power demand, shows greater variability in 2050 compared to today and becomes more compressed.** Today, as well as in 2030, this middle part of the curve continues to be dominated by fossil fuel plants, which are less weather sensitive. In 2050, on the other hand, there is a plethora of flexible generation technologies setting the price, thus we can expect greater variability in price compared to historic levels. During this period, a marginal electricity provider is typically a combined heat and power plant (CHP), a system battery, or other storage solutions.

Part 3. **The last, lower part of the curve represents periods of lower demand and high intermittent electricity generation.** This part becomes larger, and the shape is also changed towards 2050 as we see an increase in different types of responses in the market with longer periods of lower power prices from high volumes of intermittent electricity. During these periods, the marginal electricity provider is typically a solar PV or wind power plant or demand response. Uncertainties in the shape in this part lays mainly in different types of demand response, such as how flexibly electrolysers run and how smartly cars are charged. But there is also uncertainty in how wind power and solar PV plants are being operated. It can be expected that most plants will stop generation when power prices go below certain levels to optimise on O&M costs, and not be running if negative power prices as they are gradually more exposed to the wholesale prices.

In our analyses, the high share of intermittent renewables in the power system is a significant challenge, but it is manageable. There is not one solution for provision of flexibility in renewable energy systems. Instead, the needed flexibility will be provided from multiple sources and solutions. Our analysis also shows that an efficient European power grid is crucial for security of supply. The analysis stresses the importance of parallel build-out of different types of clean flexible solutions, including flexible hydropower, system batteries, demand response and high connectivity across markets. These flexible solutions have different capabilities in terms of storing or utilising electricity during periods of low prices, and producing electricity or reducing demand during periods of high prices. The business model for flexible technologies and responses is to utilise the price differences within the power market. To encourage this parallel build-out, the power market design therefore needs to ensure that electricity price fluctuations are visible for all flexibility providers, both on the supply and demand side, including consumers and prosumers.

[i] A price duration curve shows all hourly electricity prices over a year in a descending order.

The analysis stresses the importance of parallel build-out of all types of clean flexible solutions, including flexible hydropower, system batteries, demand response and high connectivity across markets.

Location: Nore hydropower plant, Buskerud, Norway

Norway is part of the European energy transition

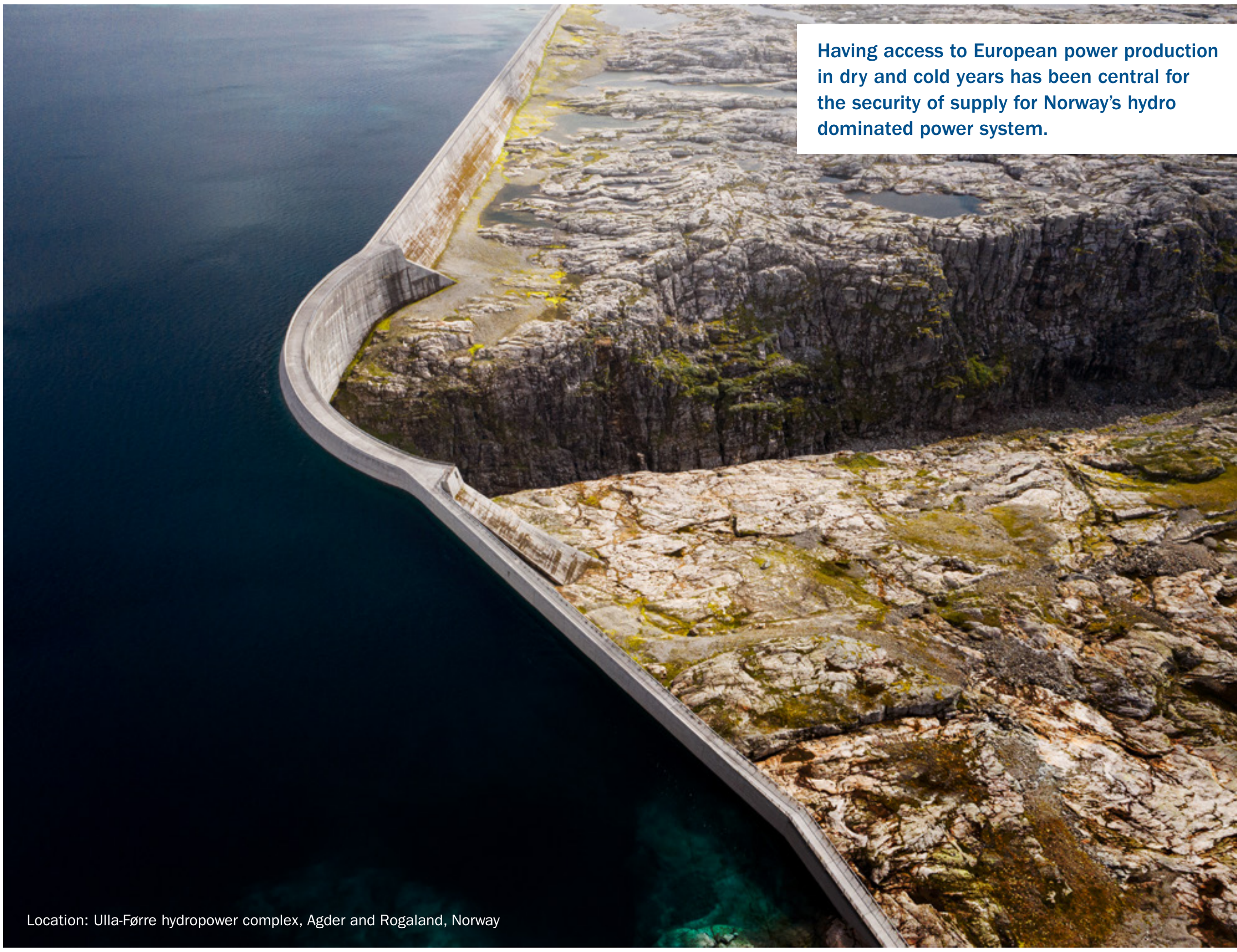
The Norwegian power system is physically connected to multiple European countries and largely regulated by the same policies and market solutions. The power flows both ways, varying between and within years. Net export from Norway in 2023 was 17.7 TWh, import was 13.2 TWh, and total export 31 TWh. Net export in 2022 was almost 5 TWh lower at 12.5 TWh, illustrating the large variability.[100]

Historically the power prices in Norway and the surrounding Nordic and European countries have been closely linked, and we expect this to continue going forward. Norway has historically had lower power prices on average than Continental Europe, including during the energy crisis (Figure 6, p.14). The future development in the European energy sector will impact power flows as well as power prices in Norway.

Currently and in the coming years, European and Norwegian power prices are largely dependent on the cost of generating gas power, which in turn is determined by gas and carbon prices. While gas and carbon prices will remain important power price drivers going forward, wind and solar power will to an increasing extent, push gas out of the generation stack and form a downwards push on European and Norwegian power prices. Increasing demand as a result of electrification will on the other hand have the opposite price impact, all else being equal. **Therefore, the net price impact of the energy transition depends largely on the rate of growth in renewable power generation capacity relative to the rate of the demand growth.** Hence, if renewable generation grows at least as fast as electricity demand, this will help to apply downwards pressure on power prices during the energy transition. When intermittent wind and solar replace dispatchable fossil fuels, price volatility is likely to increase compared to pre-crisis levels. The average power price will in addition be impacted by the price level in periods of high demand and low renewable generation (peak prices). Power system flexibility solutions, such as regulated hydropower, interconnectors, batteries, and demand response will help reduce prices in these peak hours. With more volatile prices, the value of regulated hydropower increases, and it is likely that hydropower dispatch will gradually shift from the daily consumption patterns towards providing electricity in periods with low wind and solar generation.

Access to European power production during dry and cold years has been essential to security of supply for Norway's hydro-dominant power system. From 1990 to 2019, the Norwegian hydropower inflows varied by approximately 65 TWh between dry and wet years and import from neighbouring countries during periods of low precipitation is key for security of supply.[101] A key challenge for Europe's energy security has been to ensure sufficient production capacity and access to fuel. These last years, since autumn 2021, have shown the vulnerability of the European power system depending heavily on access to Russian natural gas. **This vulnerability will be reduced as Europe transitions to a more renewable power system. This will also be positive for Norway's energy security.** At the same time, a more weather dependent European power system will pose new challenges for security of supply, – requiring greater flexibility in the power system to handle the variability of wind and solar production.

The rapid development of battery technology may remove the short-term balancing challenges to a large extent, while long periods of low wind and cloudy weather remain a significant challenge. In all cases, both historically and in the future, the power market's price signals that incentivise production and consumption to adapt to physical conditions is central for security of supply. A transition to a more weather dependent system will also mean that coupling production at different geographical locations



Location: Ulla-Førre hydropower complex, Agder and Rogaland, Norway

will have higher value. **As a result, the value of establishing grids and facilitating cross-border power exchange will continue to increase.**

Norway is also connected to the EU and UK through policies, regulations and market solutions. Regulatory changes in market design, or the configuration of bidding zones, will influence Norwegian prices. One important prerequisite for the above-mentioned price effects is the continued cooperation between Norway and EU on power market regulations. If this relationship changes, it may have significant effects on Norwegian prices, flows and security of supply.

The energy transition also affects the Norwegian power system indirectly through other policy areas. The EU is Norway's most important trade partner and export market for goods and services. In 2023 68% of Norwegian exported goods went to an EU country (87% if UK is included). Mainland exports to the EU was 58%.[102] Much of the Norwegian power intensive industry is part of European supply chains, with customers on Continental Europe. Future demand for their products in the EU will thereby also affect Norwegian power demand. EU policies for increased industrial competitiveness, like the announced Clean Industrial Deal, are important for Norway. As our analysis shows, compared to other options, a renewable dominated power system will have the lowest costs for a transition to an economy in line with climate goals. This means that fewer costs will have to be borne by European businesses and industry, which in turn also has positive effects for the market for Norwegian industrial production. Also significant for Norway, and particularly the oil and gas sector, is that we see a significant reduction in European demand for fossil fuels in all scenarios.

Norway has voluntarily joined the EU climate policy regulation to jointly reach 2030 climate targets. Through the EEA agreement Norway is already a part of important climate policy regulations like the EU ETS for industry, power, petroleum and aviation. In 2019, Norway entered a separate climate agreement with the EU. This means that Norway is an integral part of the EU climate regulation for all emissions to 2030, also those regulations that are not part of the EU ETS.

The European transition of end-use sectors represents opportunities for Norway. **Increased Norwegian renewable production will not only contribute to Norway's climate goals but can also facilitate new industrial activity.** Norway has a long industrial history, and the energy transition will give new opportunities to further develop industrial activity. Reducing greenhouse gas emissions in the industry, without decreasing the activity level, will increase electricity demand in Norway. The Norwegian Environment Agency has estimated that reaching climate goals to 2030 and 2035 means, respectively, an additional power demand of 25-27 TWh and 41-43 TWh. This does not include new industrial activity.[103] There are different estimates for demand when new activity is included, which illustrates the uncertainty. The volume of new demand will also depend on the availability of new supply. Statkraft's modelling from the Norwegian Low Emissions Report in 2023 estimated an increase of 25-55 TWh for 2030, reflecting different assumptions on industrial demand.[104]

Onshore wind power is cost competitive and relatively quick to build, but also controversial. In 2023 there were 5 GW of onshore wind power in production in Norway producing almost 14 TWh, which amounts to about 11% of total production. The Norwegian Water Resources and Energy Directorate expects no new wind to come into production in 2024 or the following two years.[105] Wind resources in Norway are excellent, and the potential is considerable (Figure 26). Public acceptance of renewable energy and the necessary infrastructure have become more important and higher on the agenda in Norway and in Europe. There are environmental and societal consequences of wind power just as there are for all energy production, and indigenous rights could also potentially be affected by power developments. New regulation in respect of new wind projects has been implemented in Norway, giving municipalities larger benefits from projects and the possibility to stop them.

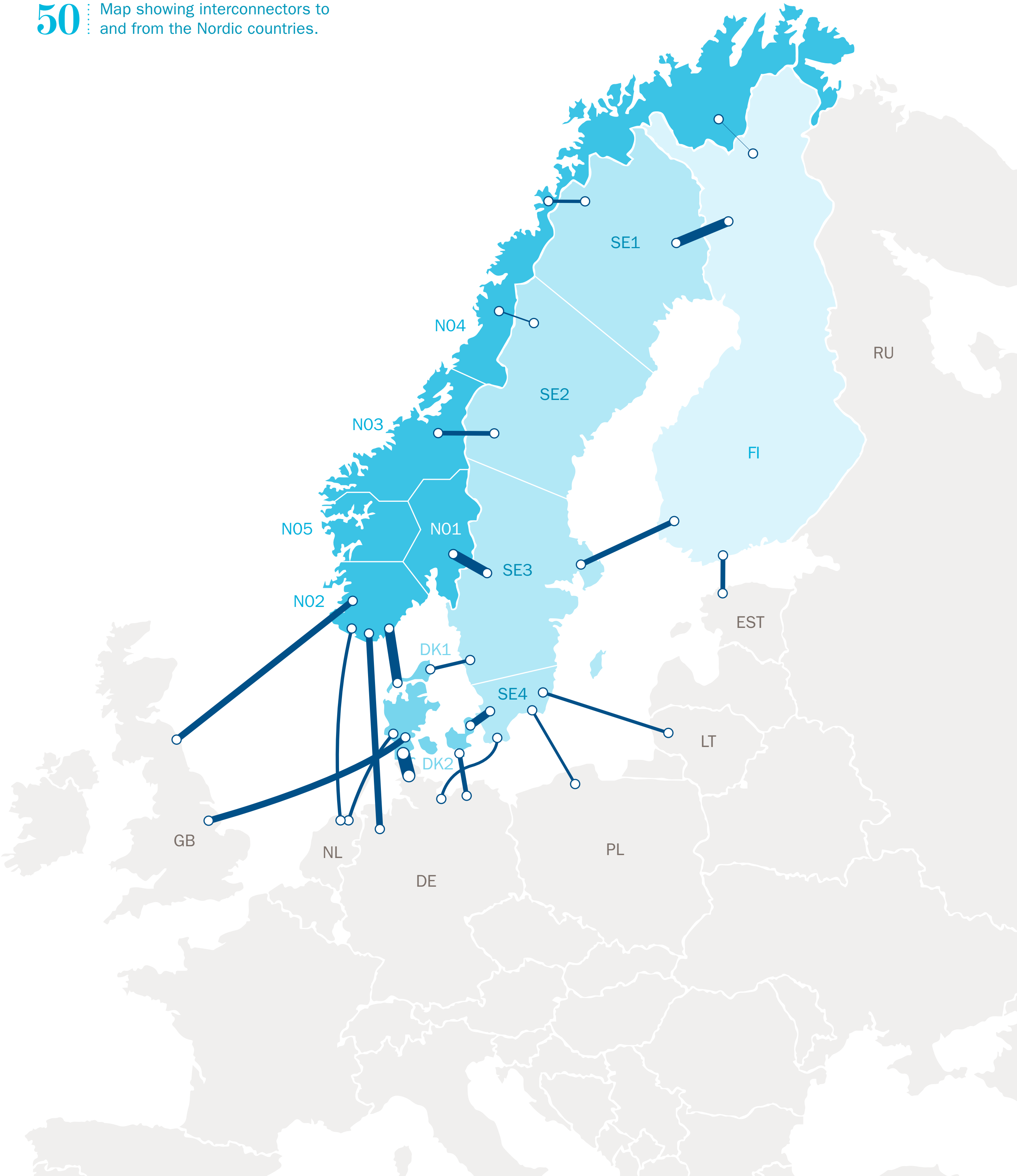
Other solutions to increase power supply, such as offshore wind, will be more costly and probably slower to get in place. There is potential also in Norway for solar power build-out. However, solar power in Norway will to a lesser degree be beneficial for the system than it would for countries further south since periods of high demand occur during winter, and Norway has less solar resources and different demand variations. Offshore wind is expected to increase, particularly after 2030, due to sinking cost, but onshore wind will - within any reasonable time-horizon - always be cheaper. Offshore wind build-out will in short-to-medium term be dependent on subsidies, but costs will decrease in the longer term. The possibility to connect offshore wind production to power grids in other countries (hybrid design) will increase the profitability of offshore wind projects in Norway.

This report shows that the energy transition will not halt as the main clean techs already have a high

Onshore wind power is cost competitive, relatively quick to build but also controversial.

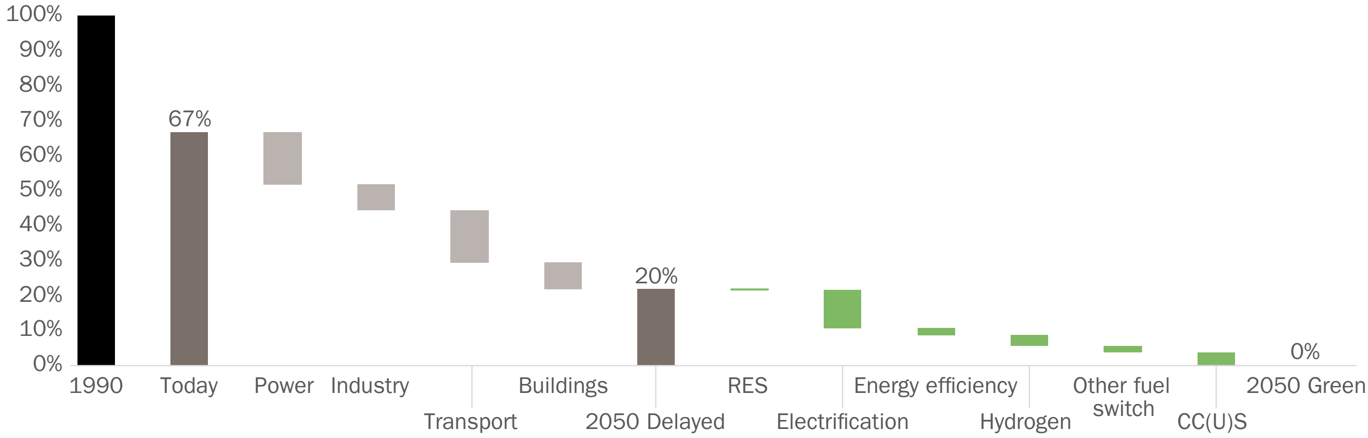
Location: Roan wind farm, Trøndelag, Norway

50 Map showing interconnectors to and from the Nordic countries.



competitiveness. Norway is part of the European transition and will be impacted in many ways. Revenues from the petroleum sector will decline, but there will also be positive effects and opportunities for Norway both directly through new business opportunities and through reduced greenhouse gas emissions. The change to emission free energy systems globally is a necessity to avoid more severe effects of climate change. It requires significant investments, but the cost of climate change will be higher. **It is important to look ahead and adapt to the challenges the transition presents, while also uncovering the opportunities. The continued close cooperation between Norway and the EU will be important to making this happen.**

51 EU emission cuts by sector from 1990 to 2050 in the *Delayed* and by solution in the *Green* scenario (% of Mt CO_2).



Closing the gap: seven solutions needed to decarbonise Europe's energy system by 2050

The energy transition in Europe will not stop, but its pace may vary, either accelerating or slowing, depending on the framework conditions shaped by both internal EU policies and external global drivers. There is already a significant energy transition in the *Delayed* scenario to 2050 (Figure 51). The difference between a *Delayed* scenario and a *Green* scenario, reaching EU's ambitious climate targets in 2050, lies in seven main decarbonisation solutions.

ONE: ACCELERATE BUILD OUT OF RENEWABLE ELECTRICITY

Both scenarios show a significant shift from fossil fuels to renewables in the power sector by 2050. The primary difference between the Delayed Transition Scenario and the Green Transition Scenario in 2050 is in the pace of renewables deployment to meet increased demand from other decarbonising sectors in the latter. This results in 52% and 38% higher wind and solar PV capacity, respectively, in the Green Transition Scenario.

Different countries face unique challenges in accelerating renewable energy deployment. However, there are common barriers that must be addressed to keep up the pace of change. These include, but are not limited to:

- Maintaining and developing a well-functioning power market that provides the correct price signals to all market actors from power suppliers all the way to producers and consumers.
- Developing flexible solutions such as energy storage, demand side management, and grid enhancements while expanding solar PV and wind power.
- Increasing grid capacity and interconnectors for efficient transfer of renewable energy.
- Resolving land use conflicts, taking into consideration environmental and social factors.
- Streamlining permitting processes for renewable projects, such as by implementing the Renewable Energy Directive (RED III) requirements in each Member State.
- Balancing supply chain diversification for security with cost efficiency. Looking ahead, gradually diversifying supply chains, without delaying the transition or adding unnecessary costs is vital.

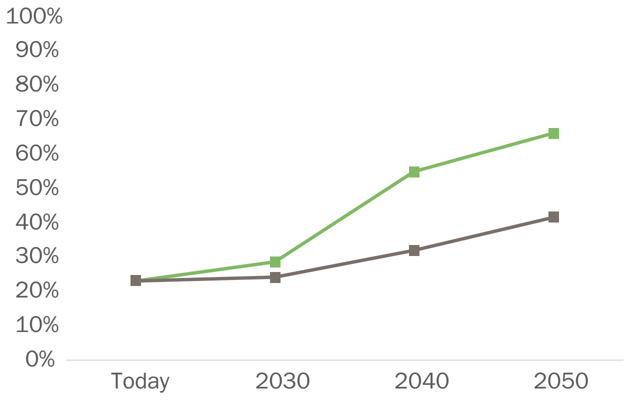
A strong collaboration and coordination between policy-makers, producers, consumers, and grid operators within and across countries will be essential for building a resilient future power system in line with the Green Transition Scenario, and to overcome the above-mentioned challenges.

TWO: BOOST ELECTRIFICATION OF END-USE

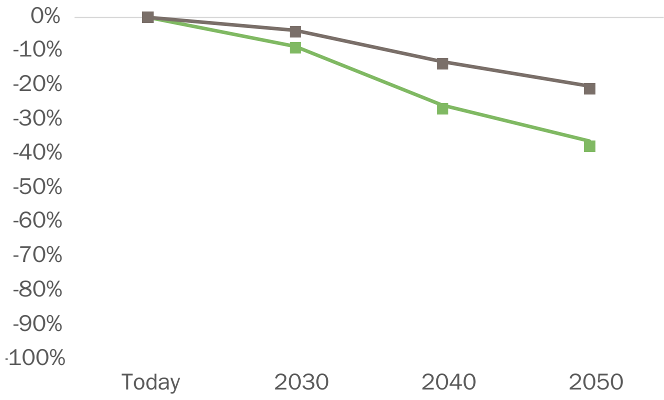
Across all end-use sectors and scenarios there is a shift from fossil fuels to electricity towards 2050. These transformations occur even faster in the Green Transition Scenario, responsible for 55% of the additional emission reductions in 2050 when comparing with the *Delayed* scenario.

To enable faster electrification, it is imperative that countries develop policies, regulations and support systems that facilitate increased use of heat pumps in buildings and industry, a shift to electric steam boilers in industry, and greater use of electric heating and cooking in buildings. For transport, a faster adoption of battery-electric vehicles and more electric-powered public transport is crucial.

52 Share of electricity in final energy demand for the Green and Delayed Transition Scenarios from today to 2050 (%).



53 Change in total final energy demand for the *Green* and *Delayed* scenarios from today to 2050 (in %).



Reducing all types of fossil fuel subsidies are beneficial for accelerating electrification and cutting emissions. Although electric cars and heat pumps are efficient solutions, these shifts are slow and not necessarily easy as they involve many decision makers, high upfront costs and infrastructural requirements.

In the Green Transition Scenario, it is assumed that policies and tax incentives are rapidly introduced in favour of electric heating and heat pumps, making these the preferred options for heating in all countries. All new buildings are built with district heating access or individual heat pumps, and countries introduce incentives to renovate and install heat pumps in older buildings where possible. Without a significant renovation to improve energy efficiency in buildings, the total demand for heating would be higher.[106]

THREE: DRIVE ENERGY EFFICIENCY AND ENCOURAGE BEHAVIOURAL CHANGE

The EU can reduce its total final energy demand by unlocking higher levels of energy efficiency through building renovations, adopting more efficient technologies and appliances, and optimise energy use with high levels of system integration. In the Green Transition Scenario, final energy demand declines by 36% by 2050, driven by increased renovation of buildings, more circularity in industry, and faster uptake of efficient heat pumps and electric cars. In addition, behavioural changes, such as car sharing, reduces the total energy demand (Figure 53).[i]

In the transport sector, emission reductions can be achieved through more electric vehicles, more efficient drivetrains and by optimising the transport of people and goods across modes, such as shifting freight from road to rail and encouraging passengers to use public transport. Increasingly automated mobility solutions combined with changes in user preferences may reap significant reductions in energy use and emissions, on top of the benefits of switching to more efficient electric cars. Electric cars will use two to four times less energy than a traditional gasoline car with an internal combustion engine.[ii]

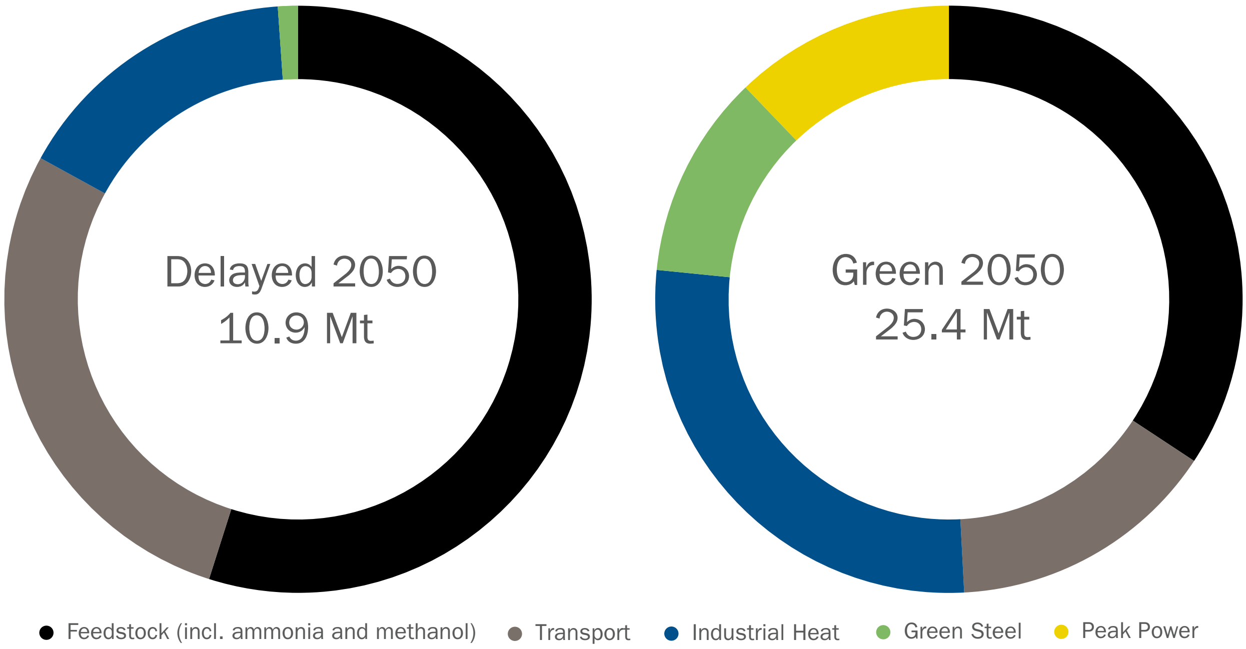
In most instances, energy efficiency results in lower energy bills for consumers and industry, less air pollution, reduced pressure on nature, and a decrease in emissions. Nevertheless, to accelerate energy efficiency, a mix of well-designed regulations, sufficient information to consumers and incentives are needed.

FOUR: DEVELOP A EUROPEAN HYDROGEN ECONOMY

In the Green Transition Scenario, clean hydrogen is responsible for 15% of the additional emission cuts in 2050 compared to the Delayed Transition Scenario. The relative contribution of green and blue hydrogen in the European market remains an uncertainty in our analysis. Green hydrogen has lower emissions and higher alignment with the EU climate goals than blue hydrogen, which is produced from fossil gas with carbon capture and storage. However, the cost of green hydrogen is dependent on future electricity prices and its deployment is dependent on the availability of renewable electricity. Blue hydrogen could provide a large-scale, baseload alternative in the medium term, however its cost is tied to future fossil gas prices, and it currently

[i] To deliver 1000 kWh of heat from heat pumps, only 200-500 kWh of electricity is needed while 1100 to 1200 kWh of gas is needed if using a gas boiler heating.
[ii] ICE cars typically use only 15% to 30% of their energy for propulsion while the remaining is lost on the way, mainly as heat. EVs can use between 60% to 90% of the energy for propulsion.

54 Yearly clean hydrogen consumption in the EU per sector in 2050 for the Green and Delayed Transition Scenarios (Mt H_2).



faces technical, economic, environmental as well as social challenges.

With less policy support in the Delayed Transition Scenario, the European clean hydrogen market grows only half as fast as in the Green Transition Scenario. The Green Transition Scenario sees growth in the hydrogen economy over the next 15 years. Annual clean hydrogen production in the EU reaches 25 Mt by 2050 (Figure 54). In 2030, first movers include existing users of grey hydrogen, primarily for fertiliser production and oil refineries, and long-haul road transport. In 2050, hydrogen demand will have diversified to more applications, including maritime transport, e-fuels, steel production, high-heat processes in industry and peak power supply. In the Delayed Transition Scenario, the distribution of hydrogen consumption is similar, however volumes are generally lower. The notable differences between the two scenarios by 2050 are that peak power is supplied by unabated gas turbines in the Delayed Transition Scenario, rather than clean hydrogen and that green steel plays a less significant role. As the value chains for hydrogen are immature, going from *Delayed* to *Green* requires strong support in the initial phase. This includes support for electrolysers, end-use applications and infrastructure, while also promoting green demand through regulations.

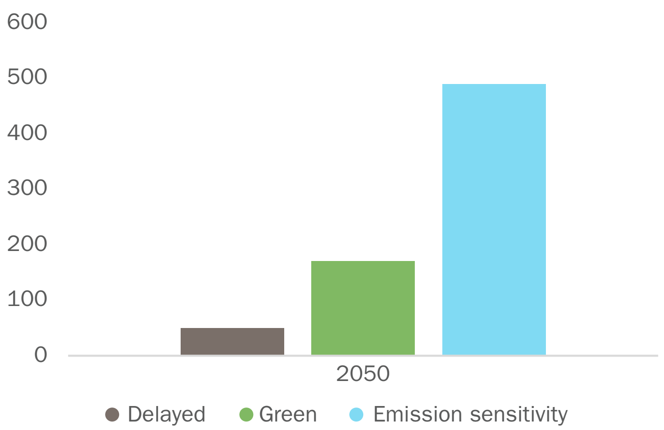
FIVE: BUILD A CARBON MANAGEMENT AND CARBON REMOVAL INDUSTRY IN EUROPE

In the Green Transition Scenario, 120 Mt CO_2 is saved in 2050 due to more carbon capture and storage compared to the Delayed Transition Scenario.

One of the major differences between the two scenarios is the deployment of carbon capture. In both scenarios, the remaining emissions in 2050 are primarily concentrated in 'hard-to-abate' industrial processes and heavy transport sectors. In the *Delayed* scenario, there is very limited carbon capture in industrial processes, negligible carbon removal deployment, and significantly lower consumption of blue hydrogen with CCS. However, in the Green Transition Scenario, there is rapid development of CCS already before 2040. As with clean hydrogen, the complete carbon management value chain from the capturing plant to a carbon storage site needs to be established. This will require support and incentive schemes.

Large deployment of industrial carbon removal and carbon capture and storage are needed as soon as 2040 to reach a 90% target. According to our analysis, blue hydrogen and the cement sectors are the largest users of carbon capture and storage. In addition, bioenergy with CCS and some direct air capture result in 100 Mt of industrial

55 Carbon capture and storage (Mt CO_2) in 2050 in the two scenarios and in a sensitivity with delayed transition to 2030, and thereafter stepping up to reach 90% emission reductions from 1990 in 2050.



Hydrogen regulations are emerging across the European value chain and there is much more clarity on the rules today than only one year ago.

Going from *Delayed* to *Green*, coal consumption in 2050 drops by 77%, the majority stemming from the blast furnace processes in the steel industry.

CO_2 removal in 2040, in the Green Transition Scenario. From 2040 to 2050 there is limited growth in CCS in this scenario according to our analysis, as emissions are already near zero, and there is greater energy efficiency and increased supply of renewable electricity at lower costs. In the Delayed Transition Scenario, there is negligible deployment of industrial carbon removal technologies over the analysis timeframe and little CCS from fossil fuels in 'hard-to-abate' industries, where CCS remains one of few viable options for reducing CO_2 emissions (Figure 55).

SIX: PHASE OUT FOSSIL FUELS WHILE MAINTAINING ENERGY SECURITY

Gas is a vital component of the European energy system today, used primarily for heating in industries and buildings and as a flexible power source. It has helped reduced EU emissions since 1990 by replacing coal, particularly in the power sector. As the cleanest fossil fuel, gas will also play an important role in Europe's transition to a net-zero energy system.

To switch fuel from coal to gas in the power sector contributes between 2%-4% of the emissions gap between the Green Transition and the Delayed Transition from 2030 to 2050. In comparing the Green Transition Scenario with the less optimistic Delayed Transition Scenario in 2050, gas use in the power sector is about 20% lower in the former. Interestingly, gas use is slightly higher in 2040 in the *Green* scenario, due to the flexible nature of gas-fired power generation, which enables the complete phase-out of coal by 2035. In the *Delayed* scenario coal remains in the power mix to beyond 2040.

Coal consumption is completely phased out of the power and buildings sector by 2035 and 2045 for the *Green* and *Delayed* scenarios. However, some coal with CCS remains in 2050 in the cement and steel industries. Shifting from the *Delayed* to the *Green* scenario, coal consumption in 2050 decreases by 77%, with most of the reduction coming from the blast furnace processes in the steel industry. Final oil consumption in energy is almost 1,000 TWh higher in *Delayed* compared to *Green* in 2050, nearly reaching zero in the *Green* scenario. The main reduction occurs in road transport, accounting for 70% of the difference, while aviation and industrial sectors each contribute 10%.

Reaching net-zero emissions requires fossil gas consumption to be substantially reduced. In the Green Transition Scenario, the power sector accounts for the largest share of gas demand in 2050, as gas provides valuable flexibility. The gas power plants have either installed carbon capture systems or are fuelled with clean hydrogen. In the Delayed Transition Scenario, gas demand falls by around 40% by 2050 (Figure 56).

While European gas demand is expected to decline in both scenarios, Europe remains highly dependent on gas imports. Liquified Natural Gas (LNG) is the most flexible source of gas supply, being able to switch between deliveries to Asia and Europe. As domestic production and pipeline imports decline, including those from Norway, LNG is anticipated to take an increasingly larger share of the European market.[i],[107]

SEVEN: FOSTER CLEAN FLEXIBILITY SOLUTIONS TO BALANCE THE ENERGY SYSTEMS

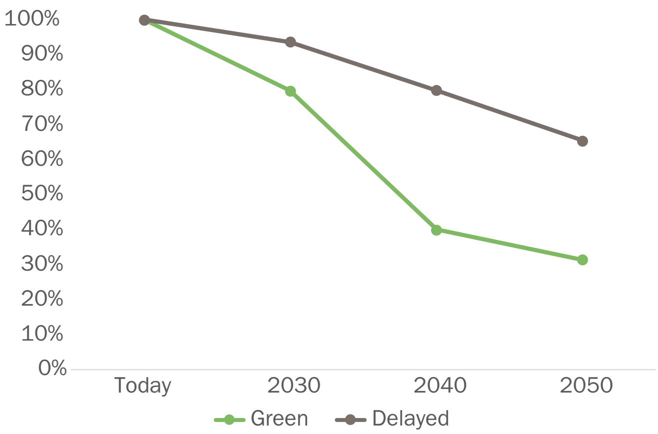
In the Green Transition Scenario, the fast build-out of a range of climate-friendly flexibility resources needs to happen in parallel with the rapid roll-out of solar and wind power generation. This requires coordinated political efforts across Member States in areas such as:

- Creating incentives for consumers to adapt their consumption according to the system needs. Providing the right price signals via the energy bills and smart meters can trigger behavioural changes. In parallel, measures to protect vulnerable consumers against energy poverty must be ensured. Demand responses from buildings, transport and industry sectors will be even more important with increased electrification.
- Build-out of sufficient national and cross-border infrastructure to benefit from the complementarity between energy systems across all timeframes. This will require close cooperation between the transmission system operators.
- Enable more flexibility on the supply side, including storage solutions, but also ensuring the right mix of variable solar and wind resources due to their complementarity.

There is no single answer to solve the flexibility challenge, but a combination of multiple solutions is needed to achieve clean and secure future energy systems.

[i] Russian gas contributed to 45% of total gas consumption in 2021 in the EU while currently providing below 15% of total gas consumption and expected to further decline.

56 Fossil gas consumption in energy in the EU today and to 2050 for the *Green* and the *Delayed* Scenarios (TWh).



Annex 1: Methodology, scenarios and key assumptions

The scenarios are developed to explore uncertainties that are central to the energy transition globally and for Europe. The purpose is to provide readers with insight into possible future energy systems and how to get there.

Statkraft's Green Transition Scenarios extend current global energy trends up to 2050. The scenarios are based on the expansion of known technologies and on Statkraft's own global and regional analyses. The analysis is not based on a linear projection of current trends, nor does it base itself on a given climate target and perform a backward analysis from this.

The Green Transition Scenario analyses the development in costs for known technologies up to 2050, including solar and wind power production, batteries, emission-free hydrogen, and so on. The scenario assumes a continued steep fall in costs per MWh and a fast pace of development.

The analyses are based on internal models as well as in-depth studies of external sources. Statkraft's Green Transition Scenarios have been prepared by Statkraft's strategic analysis team in cooperation with experts in other fields. Over 50 personnel are involved in market analysis in Statkraft.

The scenarios combine a global energy balance model and a European energy system model with insights from detailed power market models in the countries in which we are active. Statkraft models power markets in detail, hour by hour, for the Nordic countries, Europe, India, Chile, Brazil and Peru up to 2050.

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

Which emissions are covered in the Green Transition Scenario?

The emissions analysed in the scenarios are energy-related CO_2 emissions. These are emissions from fuel combustion (excluding the incineration of non-renewable waste). Other emissions that are not included are diffuse emissions (that is leaks and emissions from the transport and storage of fuels) and industrial process emissions.

Process emissions are emissions from chemical reactions in the production of, for example, chemicals, cement and certain metals. These emissions are not from combustion and cannot therefore be reduced by using electricity instead of fossil fuels. These are not included in the analyses.

CO_2 emissions from land use, land use change and forestry (LULUCF) are also excluded from the scenarios.

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

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

Non-energy CO_2 emissions from hydrogen feedstock in industry are included in the analysis, while methane emissions are excluded.

Global analyses – key output parameters compared with IEA and BNEF

TABLE 3. THE ASSUMPTIONS IN STATKRAFT'S SCENARIOS, COMPARED WITH THE IEA AND BNEF SCENARIOS.[108]

Sectors	Statkraft's Green Transition Scenario 2024	IEA STEPS (2023)	IEA Net zero (2023)	Statkraft's Delayed Transition Scenario 2024	Statkraft's Clean Tech Rivalry 2024	BNEF NEO (2024) ETS Scenario
Annual growth in primary energy demand 2021-50	-0.32%	0.52%	-0.49%	0.26%	0.16%	-0.20%
Power sector						
Demand	3.01%	2.25%	3.35%	1.46%	3.21%	2.03%
Wind power	8.59%	6.6%	9.12%	5.93%	8.32%	7.49%
Solar power	11.63%	10.2%	12.51%	7.97%	11.21%	9.22%
Hydropower	1.72%	1.35%	2.26%	1.30%	2.35%	0.46%
Unabated fossil share in power sector (TWh, 2050)	8.1%	21.06%	0.21%	23.1%	10.2%	21.98%
Primary energy and emissions						
Oil consumption: annual growth 2021-50	-2.68%	0.63%	-4.96%	-0.13%	-2.03%	-0.69%
Gas consumption: annual growth 2021-50	-1.17%	-0.04%	-5.10%	-0.31%	-0.60%	-0.37%
Coal consumption: annual growth 2021-50	-4.93%	-1.70%	-8.06%	-1.88%	-3.58%	-1.56%
Global energy-related CO_2 emissions ($GtCO_2$) in 2050	10.4	26.78	0.66	25.37	14.1	24.90

European analysis – TIMES model and key assumptions

The **Green Transition** and **Delayed Transition** Scenarios for the EU have been developed with the help of an energy system model. It represents the entire energy flow from primary supply over transformation to demand services in end-use sectors like buildings, industry and transport. Statkraft's TIMES Energy Transition (TET) model is based on the TIMES model framework developed under patronage of the International Energy Agency (IEA).[109] The TET model is a techno-economic optimisation model. It aims to supply demand for energy services at minimum total system cost by making investment decisions, as well as operating and trade decisions, under defined emission reduction targets. Input data are based on both publicly available and proprietary sources as well as Statkraft-internal insights. The main differences between the scenarios are:

Emission pathway. The Green Transition Scenario paints an optimistic yet realistic picture of the European energy transition where climate targets are met. Compared to 1990 levels, Europe achieves a 58% reduction in CO_2 emissions by 2030 and reaches net-zero by 2050. In the Delayed Transition Scenario, geopolitical tension and economic challenges de-prioritise climate action so that Europe's targets are not met in time and CO_2 emissions are reduced by 45% in 2030 and 82% in 2050, compared to 1990. In both scenarios we analyse energy-related CO_2 emissions and process emissions in the cement and steel sectors. CO_2 emissions are currently responsible for around 78% of greenhouse gas emissions excluding emissions and removals in land sectors.[i] Energy related CO_2 emissions constitute a major part of CO_2 emissions, but there are also CO_2 emissions from other industrial processes. Non-CO_2 emissions in the two European scenarios are based on the EU 2040 Impact Assessment.[110] For the Green Transition Scenario data for Land Use, Land-Use Change and Forestry (LULUCF) from the EU 2040 Impact Assessment Scenario S3 is used as input, while the Delayed Transition Scenario is based on scenario S1.

Service demand. In the Green Transition Scenario, energy efficiency measures and the heat pump build-out decrease the energy demand in the building sector while in the Delayed Transition Scenario energy efficiency loses momentum with a slower acceleration in heat pump installations. In the transport sector, the Delayed Transition Scenario sees limited EV penetration and less energy efficiency gains from car sharing and autonomous cars because consumers don't have enough incentives to change. However, in the Green Transition Scenario, transport demand is shifted away from air and road in favour of rail and ship, and public transport is to a larger degree preferred compared to the Delayed Transition Scenario. Energy efficiency measures result in a lower

Table 4: Key assumptions and input variables in TIMES model for the EU scenarios.

Parameter	Key assumptions and input variables in TIMES model for the EU scenarios
Industry energy service demand	In *Delayed* lower economic growth reduces energy service demand from the industry sector relative to *Green*. While in the *Green* economic growth is higher, but partly counterbalanced by higher focus on sustainable material use and circularity. Overall, the demand for energy services in industry are a few percentages higher in *Green*.
Buildings energy service demand	Emphasis on energy efficiency and insulation of buildings in *Green* gives significantly lower demand for energy services in the building sector compared to *Delayed* to 2050. In addition, there is slower uptake of heat pumps in *Delayed*.
Transport energy service demand	In *Green* demand for air transport is lower as more personal travel is transferred to other modes of transport. Higher trade and economic growth increase demand for transport services in this scenario compared to *Delayed* even though there is more car sharing and automated vehicles. In summary, demand for personal transport and freight is almost equal between the two scenarios.
CO_2 emissions (% reduction from 1990-level)	The Green Transition Scenario reaches 58% CO_2-emission reductions by 2030 and 100% by 2050 from 1990-levels. This compares to 45% and 82% in the Delayed Transition Scenario. This is slightly more ambitious than when considering all GHG-emissions.
RES technology costs	In *Green* the technology costs for solar PV, onshore wind and offshore wind are significantly lower than in the *Delayed* due to higher global deployment, little supply chain restrictions, less need for regional supply chains and in general fewer barriers and conflicts at national and local levels.

The Green Transition Scenario paints an optimistic yet realistic picture of the European energy transition where climate targets are met. Compared to 1990 levels, Europe achieves a 58% reduction in CO_2 emissions by 2030 and reaches net-zero by 2050.

Location: Ulla-Førre hydropower complex, Aust-Agder and Rogaland, Norway

energy demand for agriculture and industrial heat in the Green Transition Scenario compared to the Delayed Transition Scenario. Hydrogen demand as a feedstock, though, is almost twice as high in 2050 in the Green Transition Scenario as in the Delayed Transition Scenario.

Clean technologies. Build-out potentials for wind and solar power are lower in the Delayed Transition Scenario as they are met with more public opposition and less political support. Lower installation volumes in combination with geopolitical tensions also lead to higher costs. Solar and wind capacity additions in the Delayed Transition Scenario are, respectively, 45% and 60% more expensive, than in the Green Transition Scenario. The same applies to electrolysers which are 80% more expensive in the Delayed Transition Scenario.

[i] Methane, N_2O and F-gases are responsible for 13.5%, 6% and 2.3% respectively. In addition, there are emissions and removals from land use and land-use changes.

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Location: Ulla-Førre hydropower complex, Aust-Agder and Rogaland, Norway