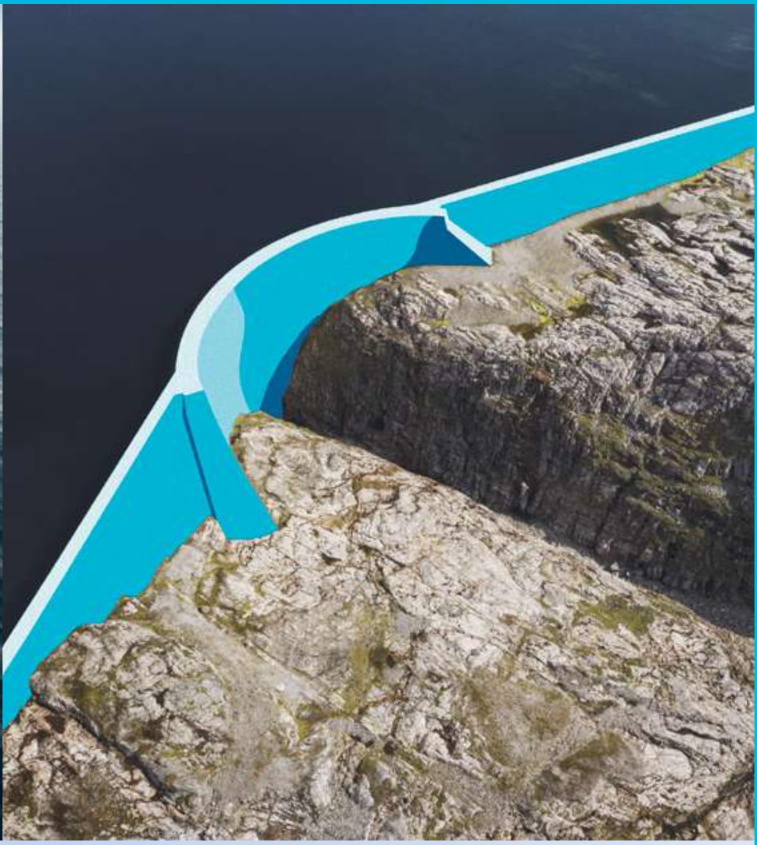
Statkraft

2023

Low Emissions Scenario



Contents

Optimism in times of uncertainty

Christian Rynning-Tønnesen

We are living in an era of unprecedented change. Ongoing conflicts, such as Russia's invasion of Ukraine and the war between Hamas and Israel, and increasing tension between China and the US, are reshaping the global geopolitical dynamic. Key trends since 1990 are shifting due to geopolitical tensions and policy-driven economic fragmentation. Furthermore, we are also facing challenges like high inflation, rising interest rates, and significant demographic shifts, with India becoming the world's most populous nation.

Simultaneously, extreme weather events are increasing in frequency and severity worldwide. In 2023, record high temperatures, alongside dry and windy conditions, contributed to wildfires, and heavy rain caused severe flooding. These events underscore the urgent consequences of climate change. It is now more critical than ever to curb the current trajectory.

These changes have a profound impact on the energy transition, leading to heightened uncertainty. However, rather than halting the energy transition, we have observed an acceleration of renewable energy deployment due to an increased focus on security of supply, climate concerns and the growing competitiveness of solar and wind power.

In response to the growing uncertainty, the 8th edition of Statkraft's Low Emissions Scenario introduces two additional scenarios to explore the challenges and consequences of alternative paths: "Clean Tech Rivalry", influenced by a more protectionist transition in the US, EU and China, and "Delayed Transition", where less climate attention in times of increased conflict and cost-of-living leads to a slower transition.

Statkraft's analysis points to the energy transition continuing across all scenarios. The affordability of solar PV, onshore wind, batteries, and heat pumps is driving transformative changes in energy production and consumption. Our findings suggest that wind and solar will continue to outcompete fossil technologies across all three scenarios. Due to rising fossil fuel prices, these technologies have maintained their competitiveness despite inflation. Now, we are witnessing that costs are starting to decline again.

The Low Emissions Scenario remains an optimistic yet realistic scenario, largely driven by a stronger trend in favour of more solar PV and wind power than previous years. The Low Emissions Scenario predicts that renewable energy will supply over 80 per cent of the world's power demand in 2050, more than doubling over the timeframe due to deep electrification of buildings, transport and industry. With this as a backdrop, we can assume just below 2 degrees warming.

Even if Statkraft's Low Emissions Scenario becomes reality, global emissions will still fall short of aligning with a net-zero future. While renewable energy is growing fast worldwide, there remains a need to overcome increasing external uncertainties and internal obstacles. To expedite the energy transition, we should expand on proven strategies. At COP 28, the focus on tripling renewable capacity is crucial, given the cost-effectiveness of wind and solar power as mitigation measures. Until now, the energy transition has predominantly occurred in the developed world and China. Going forward, it is crucial to also accelerate the energy transition in regions with limited access to capital and technology, where most of the energy demand growth is expected. Additionally, we need to invest in and develop less mature mitigation measures, such as hydrogen and Carbon Capture, Utilisation and Storage (CCUS).

There is still a small window of opportunity to accelerate the current trajectory. Achieving net-zero emissions by 2050 requires accelerated action on all fronts and global collaboration is vital. Statkraft's Low Emissions Scenario is still well within reach. Let us use this momentum to propel ourselves even further towards a net zero future.

Location: Devoll Dam, Albania

SUMMARY OF

Statkraft's Low Emissions Scenario 2023

Statkraft's Low Emissions Scenario is an optimistic but realistic assessment of global energy trends up to 2050. The scenario analysis is developed by analysts leveraging the knowledge of more than 50 internal experts and their work to model power markets in detail across 21 countries.

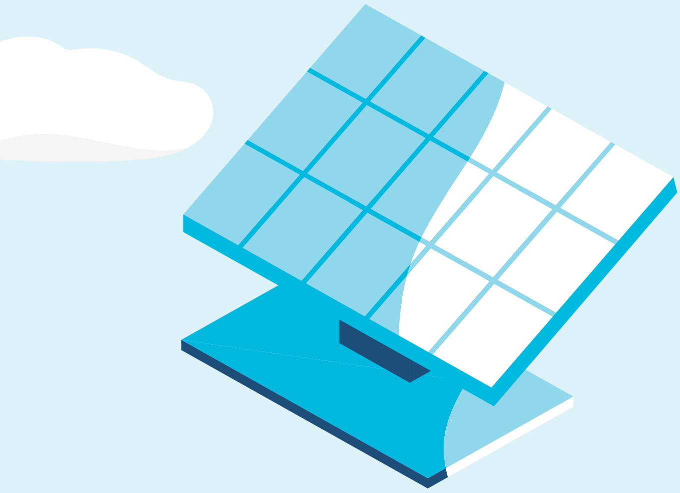
In response to growing global uncertainty, this year's Low Emissions Scenario also features two additional scenarios: Clean Tech Rivalry and the Delayed Transition.

Competitive clean tech and energy security drive decarbonisation

Clean energy technologies like wind and solar power, and batteries have seen a 70 to 90 per cent cost reduction over the past decade, making them competitive with fossil fuels. Battery electric vehicles and heat pumps are also nearing cost parity. In addition, recent market turmoil and geopolitical tensions have increased global focus on energy security, spurring stronger policies for renewable energy deployment and energy efficiency.

In this context, the Low Emissions Scenario projects strong growth in solar and wind power, even beyond the 2022 report. By 2050, solar and wind power are expected to increase 22 and 12 times respectively, driven by competitiveness and supported by energy security and climate policies. Deep electrification and green hydrogen in transport, industries, and buildings more than double global electricity consumption by 2050 in the Low Emissions Scenario. Primary energy consumption, on the other hand, decreases slightly due to increased energy efficiency and electrification.

The Low Emissions Scenario projects an emissions pathway that limits global warming to below 2 °C, at a pace somewhat faster than last year's projections.



Additional scenarios explore alternative transition pathways

Increasing global fragmentation could challenge the pace and scope of the energy transition. Climate change mitigation has so far relied on extensive global trade and adequate supply chains for clean energy technologies and raw materials. Global collaboration also bolsters technology development, economic efficiency, and necessary financing for the energy transition. Emergence of new societal challenges and increased geopolitical tension could, however, lead to more protectionism that may affect the global energy transition more than previously anticipated. With the current economic and geopolitical challenges, the uncertainty surrounding the pace of the global energy transition seems greater than before. Against this background, Statkraft analyses two additional scenarios called the Delayed Transition and the Clean Tech Rivalry scenarios in this year's report.

In the Clean Tech Rivalry scenario, subsidies spur a clean energy transition, but at higher costs and with delays

In the Clean Tech Rivalry scenario, we assume that global powerhouses like the US, EU, and China engage in a subsidy-fueled competition for dominance in clean energy supply chains. In this scenario, building and safeguarding regional supply chains is emphasised, resulting in less global trade for materials and technologies crucial to the energy transition. A subsidies-led transition can lead to a less efficient transition with higher shares of technologies like nuclear and Carbon Capture, Utilisation and Storage (CCUS). Despite delays and higher costs, the energy transition gradually gains momentum in the Clean Tech Rivalry scenario as regional supply chains develop, and towards 2050, solar and wind volumes grow 20 and 10 times, respectively. However, this scenario results in 20 per cent higher energy-related CO_2 emissions in 2050 compared to the Low Emissions Scenario, and 15 per cent higher cumulative emissions from 2021 to 2050.

In the Delayed Transition scenario, conflicts and unrest slow, but don't halt, the clean energy transition

The Delayed Transition scenario assumes that the energy transition is lower on the political agenda as conflict, social unrest, and higher costs of living take precedence. As global geopolitical tensions escalate, national and energy security concerns come to the fore, and fossil-fuel technologies with lower upfront costs remain a larger part of the energy mix for longer. This may slow the energy transition, but will not halt it entirely, since cost-efficient wind and solar power remain competitive. Even in this scenario, solar and wind power generation grow 6.5 times to 2050. Electrification develops at a reduced pace compared to the Low Emissions Scenario, especially in sectors where strong proactive policies are still needed. Less mature technologies like hydrogen and CCUS barely reach deployment by 2050. This results in 130 per cent higher energy-related CO_2 emissions in 2050 compared to the Low Emissions Scenario, and 30 per cent higher cumulative emissions from 2021 to 2050.

To reach net zero by 2050, we need more of everything and faster

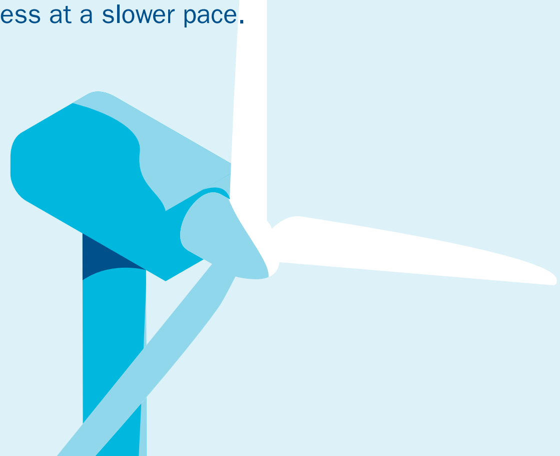
In the Low Emissions Scenario, emissions drop by nearly 70 per cent by 2050, falling short of the Paris Agreement's targets. To meet these climate targets, wind and solar energy deployment must accelerate even faster. The gap in wind and solar generation between Statkraft's Low Emissions Scenario and the IEA's Net Zero Roadmap is about 20 per cent in 2030 and 2050. Electrification must also speed up and scale wider, with more efficient energy use. The key difference between the Low Emissions scenarios and IEA's Net Zero Roadmap lies, however, in the deployment of immature technologies like hydrogen and CCUS in hard-to-abate sectors. These technologies grow two to three times faster in the IEA's Net Zero Roadmap.

The European energy transition is inevitable

The report delves specifically into the clean energy transition of the European energy system. In all scenarios, the energy transition is inevitable. In the Low Emissions Scenario, Europe meets its 2030 RePower EU targets of reducing emissions by 55 per cent without Russian gas. This is primarily achieved through the deployment of renewable energy, energy efficiency and electrification in transport and heating. Solar power deployment may reach or even exceed the targets set in REPowerEU while the wind power target appears more challenging.
Wind and solar power replacing fossil fuels is the dominating emission reduction solution towards 2030, while electrification and hydrogen growth is strongest in the latter half of the period to 2050.

A clean energy transition serves multiple objectives

A conflicted world may add substantial hurdles on the path to a clean energy system. At the same time, the energy crisis illustrated the risks and vulnerability in the dependence on fossil fuels supplied from unstable regimes. This report shows that a fast, clean energy transition, as in the Low Emissions Scenario, may both mitigate climate change and contribute to the development of resilient energy systems. Renewable energy is a key to the energy trilemma of sustainability, affordability, and supply security. The report also concludes that even in a more conflicted world, renewable energy growth remains strong and does not reverse under any scenario; it may just progress at a slower pace.

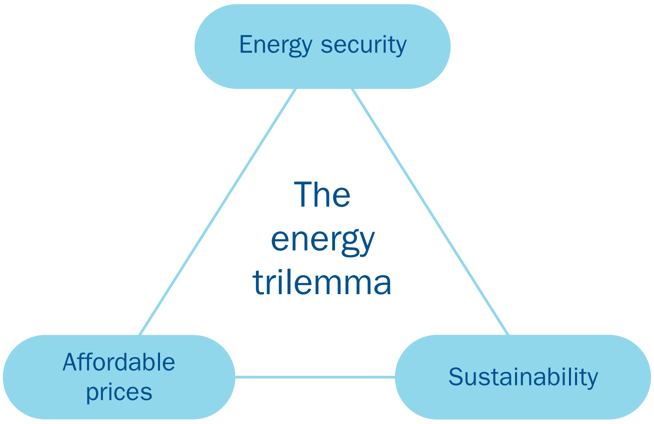


CHAPTER 1

The stakes have been raised in the energy transition

Location: Ringedals Dam, Norway

The way we generate and use energy is in transition, primarily driven by climate policies and the falling cost of renewable technologies. Furthermore, Europe recently experienced an energy crisis due to the reduced supply of Russian fossil gas, which highlights the critical importance of secure and affordable energy. As stated by the International Energy Agency (IEA): a clean energy transition based on renewable electricity and electrification will not only reduce emissions but also ensure a resilient energy supply.[1] As such, it is not surprising that the deployment of renewable energy has accelerated in response to the energy crisis. Ambitious plans such as the REPowerEU[i] and the IRA[ii] in the United States demonstrate strong commitment to this transition.
For the first time in history (outside of a recession), clean power growth is likely to exceed electricity consumption growth in 2023, suggesting that global power sector emissions will peak this year.[2] This year, solar power is set to attract more capital than oil production for the first time, with a total of 1.7 trillion to be invested globally in clean technologies in 2023, which is 70 per cent more than the investment in fossil fuels in the same period.[3]



At the same time, the shift from a fuel-intensive to a material-intensive energy system creates new dependencies. China's dominance in clean energy supply chains highlights new concerns, such as the need for diversification and greater domestic clean industry development. Another cause for concern is how the developing part of the world risks lagging in the energy transition. Developing countries are struggling to keep pace, primarily due to limited access to capital and clean energy technologies. Investments remain concentrated in the developed countries and China. Increased geo-political tension has also led to increased global attention on these concerns, as less global collaboration and trade could delay the needed energy transition.

In addition to the climate crisis, many ecosystems are under pressure globally and pollution continues to harm health and the environment. The need to address these challenges has been lifted higher on the agenda within the Kunming-Montreal biodiversity agreement.[4]

Over the last year, extreme weather events around the world have once again served as reminders of the potentially major implications of climate change.

In 2023, the Earth experienced its three hottest months on record.[5] There have been record breaking heat waves in North Africa, Japan, and Turkey. Warm, windy, and dry weather has led to wildfires in Spain, Greece, and Hawaii. In Norway, the extreme weather "Hans" caused severe flooding. Climate change is already making insurance more expensive, and parts of the world are simply uninsurable due to the increased frequency and severity of natural disasters.[6] According to the IPCC, the global temperature is already 1.1 °C higher compared to pre-industrial times, and it will continue to rise as long as fossil carbon is emitted to the atmosphere.[7]

While the classic trilemma of energy security, affordability, and environmental sustainability (Figure 1) is still highly relevant, there are also other important trade-offs in a sustainable energy transition. Environmental sustainability is not only about climate but also land use, pollution, and the protection of endangered species. Security of supply is not only a technical issue but also one of national and regional security interest. And affordability is not only about consumers, but also the total cost of providing energy to society. In a sense, all parts of the energy trilemma have become more important, and therefore handling the trade-offs correctly is even more necessary. At the same time, due to the urgent need for climate action, the cost of inaction runs high.

Renewable energy offers, to a large degree, a holistic solution to the classic energy trilemma, one that addresses the three crucial aspects: energy security, environmental sustainability, and affordability.

It contributes to diversifying energy sources, reducing dependence on specific suppliers, lowering greenhouse gases to meet environmental goals, and increasing cost-competitiveness for consumers. Even if an energy system based on variable renewable generation is vulnerable to weather driven fluctuations in electricity supply, there are several solutions that handle these fluctuations. Overall, renewables play a pivotal role in enhancing energy security, sustainability, and economic feasibility in our Low Emissions Scenario.

In the following chapters, we discuss important trends that may affect the clean energy transition, along the three facets of the energy trilemma: energy security, environmental sustainability, and affordability.

The geopolitical changes in recent years have sparked greater political uncertainty. To explore the potential outcomes, we have introduced two additional scenarios in this year's report: a subsidies race scenario, or Clean Tech Rivalry, in which we will experience less global trade but a big push for the energy transition, and the Delayed Transition scenario, which would entail less global trade and a slower energy transition. However, the extrapolation of the most important trends in the energy transition still points towards a rapid shift towards clean energy.

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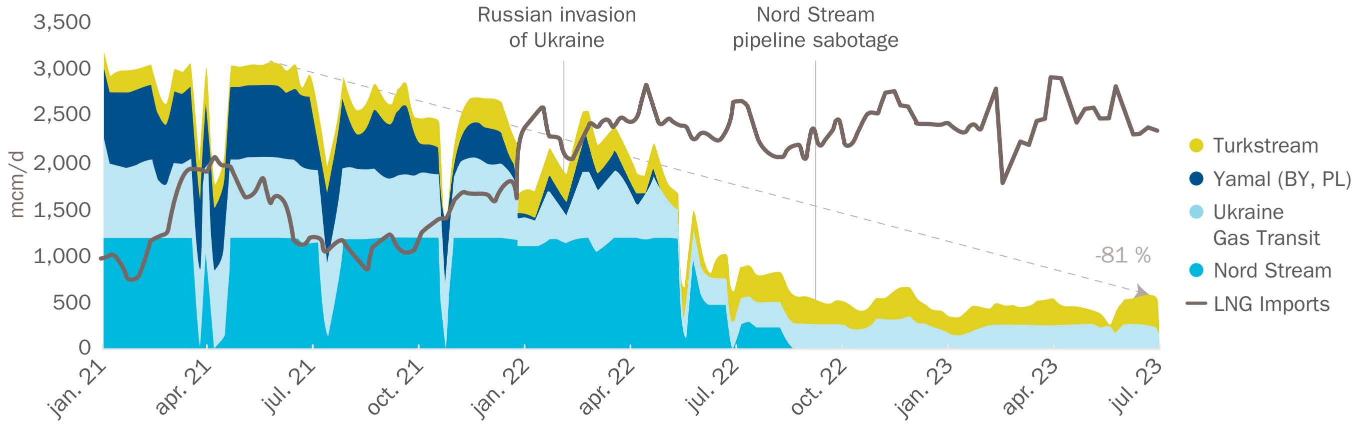
[i] The REPowerEU plan, launched in May 2022, is an ambitious plan to rapidly reduce gas demand in a bid to reduce Europe's dependence on Russian gas imports, accelerating energy efficiency, electrification, hydrogen and renewables deployment. The plan builds on the EUs "Fit for 55" legislative package, launched in July 2021, which is the EU's framework for how to reach the 2030 and 2050 climate targets.

[ii] See fact box "US' response: IRA".

2 Russian fossil gas flows and LNG imports to Europe, 2021 to July 2023 (mcm/d)[8]

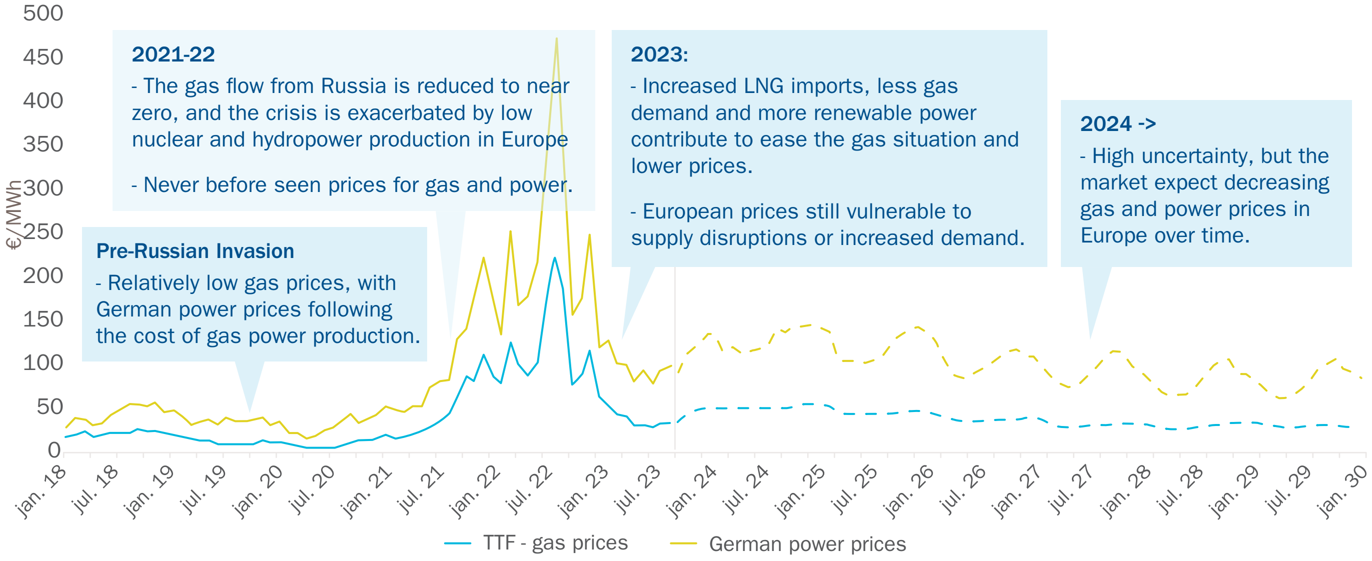


Energy security imperative

During the global economic recovery following COVID-19, the markets for several fuels were affected by a tight balance between supply and demand. In 2021 and 2022, large parts of the world experienced an energy crisis, as Russian exports of gas to Europe began to decline prior to their invasion of Ukraine (Figure 2). From April 2021 to August 2022, the prices for gas and power surged dramatically, reaching an astonishing eleven-fold and nine-fold increase, respectively. This challenging energy landscape was further compounded by a decline in nuclear power production. This was mainly caused by problems in French nuclear power plants and low precipitation levels in the Alps in 2022, which also led to reduced output from hydropower plants.[10] The combination of these factors further exacerbated the energy crisis in Europe, causing significant strain on energy supply.

The European energy system was incredibly stressed during 2022, as Europe ran the risk of depleting its gas supply during peak winter demand. However, reduced demand from households and industry, along with fuel-switching and increased LNG imports, prevented an energy shortage in Europe. The rather mild winter also reduced the risk of a shortage, as the number of heating days in the EU fell by 12 per cent in 2022 compared to 2021. Currently, the European gas balance prior to the winter season of 2023/24 is in a less severe state than the two previous years, due to bolstered gas reserves in anticipation of higher demand.[11] However, an unusually cold winter and/or further disruptions in the supply chain could potentially put Europe in a precarious position once again in terms of its energy supply.

3 European gas prices and German power prices 2018 - 2023 and forward prices as of September 2023 (€/MWh)[9]



2021-22

- The gas flow from Russia is reduced to near zero, and the crisis is exacerbated by low nuclear and hydropower production in Europe

- Never before seen prices for gas and power.

Pre-Russian Invasion

- Relatively low gas prices, with German power prices following the cost of gas power production.

2023:

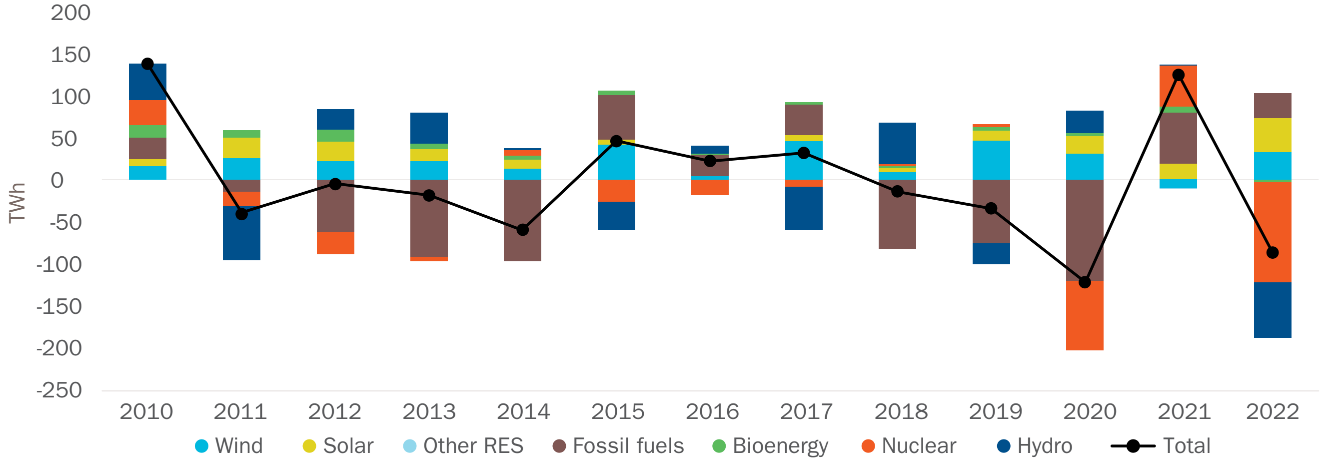
- Increased LNG imports, less gas demand and more renewable power contribute to ease the gas situation and lower prices.

- European prices still vulnerable to supply disruptions or increased demand.

2024 ->

- High uncertainty, but the market expect decreasing gas and power prices in Europe over time.

4 Yearly change in power generation (TWh) per technology in the EU from 2010 to 2022[14]



Energy crisis accelerates renewable deployment

Installation of renewable capacity so far has accelerated during and after the energy crisis, despite inflated costs. For example, renewable capacity experienced a record-breaking increase in 2022, with approximately 340 GW added worldwide.[12] Solar PV was the main contributor to this growth, due to net additions of nearly 220 GW - with China and the EU accounting for 85 per cent of this growth. In the US, capacity growth declined, as a result of the country's struggle with supply chains and rising costs. Growth in global wind capacity also fell, as COVID restrictions in China and supply-chain limitations hampered growth. The trend has continued into 2023, with solar investment on the rise and wind investment in decline.[13]

Europe installed 50 GW of new renewable capacity in 2022, which contributed to a reduction in gas consumption of around 11 billion cubic meters.[15] However, despite impressive renewables growth in Europe, gas and coal power generation also increased slightly in 2022, due to the continent's struggle with nuclear outages and low hydro generation. So far in 2023, fossil fuel generation is substantially lower than the same period last year.[16]

According to the IEA, investments in clean energy increased by 206 billion dollars from 2021 to 2022, reaching a total of 1,617 billion dollars. The IEA expects this to continue in 2023, with investments amounting to 1,740 billion dollars, the equivalent of 1.70 dollars in clean energy for every dollar invested in fossil fuels. Five years ago, this ratio was 1 to 1.[17]

Renewable capacity experienced a record-breaking increase in 2022, with approximately 340 GW added worldwide. Solar PV was the main contributor to this growth, due to net additions of nearly 220 GW

Location: Alcalá de Guadaira, Seville, Spain

In 2021, 96 per cent of solar panel wafers and 92 per cent of anodes to electric cars batteries were produced in China

Still competitive despite cost increase

The strong growth in renewables has materialised despite increased costs caused by inflation and supply chain disruption. In fact, the extreme increase in fossil fuel prices has contributed to preserving and even enhancing renewables' competitiveness. In 2022, the global weighted average levelised cost of electricity (LCOE) was 52 per cent and 29 per cent lower than the cheapest fossil fuel solutions for new onshore wind projects and new solar PV projects, respectively.[18] Recently, prices for important renewable technology inputs, such as steel and polysilicon, have declined since the peak in 2021.[19] Over time,this will contribute to further moderating the cost of renewable technology.

Sufficient investment in supply chains for clean energy is pivotal for continued cost reductions. For some parts of the clean energy supply chain, such as solar PV and battery production, the announced production capacity is already in line with what is necessary in IEA's Net Zero Scenario.[20] However, for other parts of the supply chains, higher investment levels are necessary. Although there are several types of supply risks for clean technology materials, there are ample resources available to cover future demand growth. Given the right price signals and government support, sufficient investment will stimulate supply growth. Long lead times for production could result in volatile metal prices in the years to come, but this is unlikely to be significant enough to derail the energy transition.

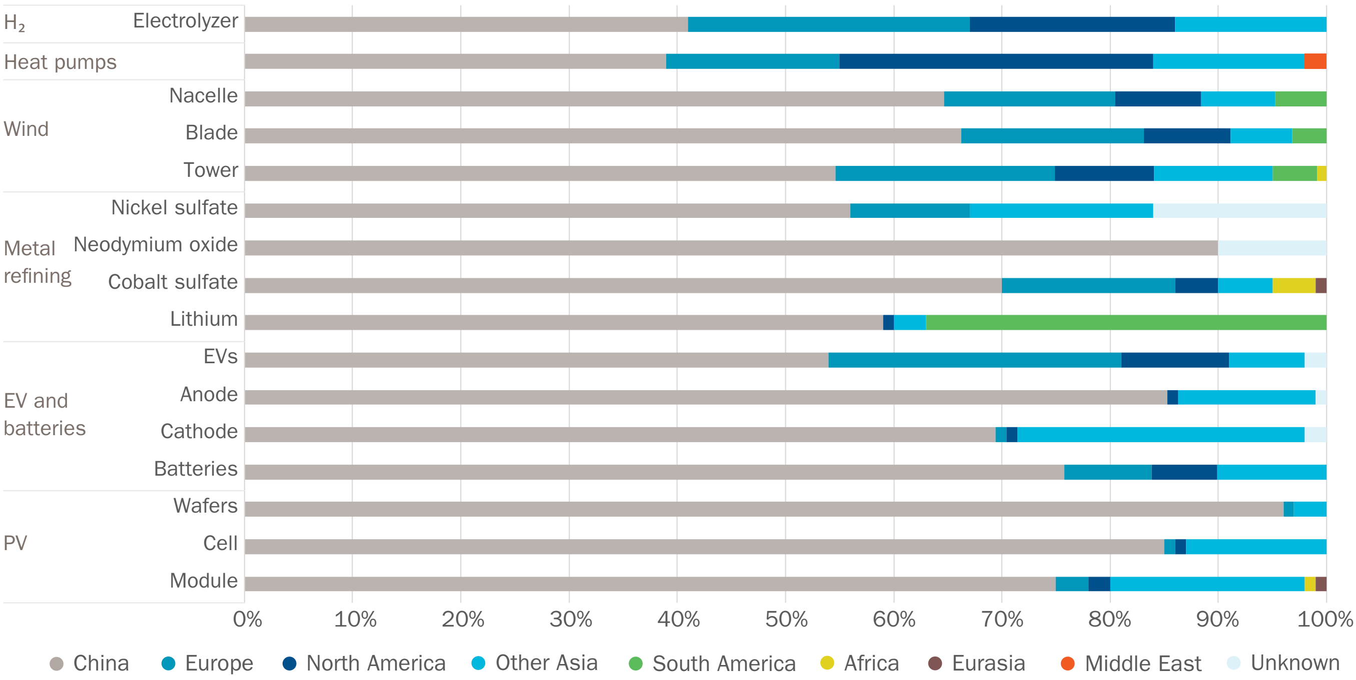
Resilience of supply chains

Increased emphasis on security of supply has directed more focus to creating renewable supply chains in areas where China today holds a dominant position – particularly in manufacturing, refining, and production of several critical raw materials. For the refining of rare-earth minerals and in the supply chains for solar and batteries, China has near total dominance. In 2021, 96 per cent of solar panel wafers and 92 per cent of anodes for electric cars batteries were produced in China (Figure 5). Around 90 per cent of rare earth minerals were refined in China as well.[22] On the mining side, greater diversification is expected with new mines entering the market in the coming years. However, for refining and processing, the geographical concentration is expected to become even greater. According to the IEA[23], three layers of supply challenges need to be addressed related to materials critical to the energy transition:

1) Whether future supplies can keep up with the rapid pace of demand growth in climate-driven scenarios
2) Whether those supplies come from diversified sources
3) Whether those volumes can be sourced in a sustainable way.

Policies such as the Inflation Reduction Act (see **Fact Box**) are channeling more funds into clean energy technologies, with the dual purpose of cutting emissions while simultaneously supporting local supply chains. We currently observe the increased willingness to support renewable technology on one side, and a push towards increased protectionism and trade barriers on the other side. For now, the higher costs are offset by increased subsidies and the availability of government funds to support the transition. This has accelerated the energy transition; however, this approach could result in a more costly transition. Research shows that both the short-term and long-term costs of decoupling global supply chains are high.[24]

5 Clean energy manufacturing capacity by location (%)[21]



FACT BOX

China's role in the Energy Transition

The story of China's growth has been one of the most important trends shaping the global economy and political order over the last decades. This story also includes the massive expansion of the power sector, including enormous investments made in renewable energy. In 2023, the China Photovoltaic Industry Association forecasted that between 120 to 140 GW solar will be installed in China. That tops the record of 87.4 GW installed in 2022. There has also been an impressive growth in onshore and offshore wind, and China accounted for 49 per cent of global renewable addition.[25] In addition, 4.4 million battery electric vehicles were sold in the country.[26]

This deployment has been enabled by domestic renewables supply chains. China holds a large market share in nearly all renewable technologies, with almost complete dominance in solar, battery and refining of rare-earth minerals.

China's dominant position makes it near impossible to find alternative suppliers. Even when sourcing from other countries, including Vietnam, Malaysia, or the US, manufacturers typically rely on subcontractors from China.[27]

The rising tension between China and the US has significant implications for renewable energy supply chains. Russia's invasion of Ukraine has been a reminder that energy supply can be weaponised. This has stoked fears that China can weaponise its dominance in renewable energy to extract concessions from the West. In addition, there are questions about sustainability and human rights abuses in Chinese supply chains. In 2023, there has been a clampdown on firms doing due diligence in China, making it harder to certify whether products have been made according to ESG (Environment, Social and Governance) standards. [28]

In July 2023, China limited the export of the rare-earth minerals germanium and gallium in a move seen as retaliatory to the US's limitation on export of advanced semiconductors to China.[29] These minerals are used in production of semiconductors and for some renewable technologies.

With increased emphasis on security of supply in the energy sector and increased tensions with China leading to calls for de-risking, we have seen a policy shift in both the US and EU. With the US's "Inflation Reduction Act" and EU's "Green Deal Industrial Plan", green policies have evolved from reducing emissions to now also ensuring some degree of domestic control over supply chains.[30] Domestic jobs and growing local economies have been used as arguments for a green transition. Now security of supply has been added as an important driver.

We see similar trends in other parts of the world. India has the Production Linked Incentive (PLI) scheme to support domestic manufacturing of solar PV production.[31] In October 2022, the program entered its second phase in which it was scaled up from 600 million dollars in the first phase to 2.4 billion dollars in the second phase. In 2021, India also launched a PLI for Advanced Chemistry Cell Battery Storage and has allocated 2.2 billion US dollars to support domestic manufacturing of batteries. Canada, South Korea, Japan, and Australia are other examples of countries that have recently granted public subsidies to support domestic manufacturing of renewable technology.[32]

THE US' RESPONSE

Inflation Reduction Act

The Inflation Reduction Act (IRA) is a set of legislations that address several different issues, including deficit reduction, healthcare, and climate. It is the most sweeping climate legislation ever passed by the US Congress, and it will direct more than 369 billion dollars in loans and grants to climate and energy security programs over the next ten years.[33] It includes support for a broad range of technologies, including the deployment of renewable energy, nuclear power, carbon capture, and storage, and clean hydrogen.[34] With the passage of the IRA, US emissions are forecasted to decline by 40 per cent compared to 2005, bringing the US closer to achieving its target of reducing emissions by 50-52 per cent below 2005 levels by 2030.[35]

The IRA is noticeable due to its strong emphasis on support for manufacturing and local content. Facilities and projects that are eligible for support can receive higher subsidies if they meet local content requirements.[36]

The law also includes plans for permitting reforms. According to Berkeley Lab, there were close to 2000 GW of renewable capacity and storage applying for interconnection in 2022, including 947 GW solar power capacity and 300 GW of wind. [37] Ensuring that there is built transmission to integrate new capacity is necessary for the support in IRA to have effect. The same goes for the permitting for new renewable energy projects.

EU'S RESPONSE

Green Deal Industrial Plan, Net Zero Industry Act and The Critical Raw Materials Act

In February 2023, the European Commission presented the **Green Deal Industrial Plan (GDIP).**[38] This is a response to the changing geopolitical context and the political wish to increase Europe's competitiveness and reduce supply chain dependencies on countries such as China. Under its four pillars – regulation, financing, skills, and trade – the plan sets out key policy goals for:

- securing the supply of clean technologies and critical raw materials
- stepping up investments in innovation and deployment of green technologies, and create lead markets by deploying regulations on the Single Market
- using public procurement and competition policy in a more strategic way
- creating new and strengthening existing international partnerships with countries the EU considers as "friendly partners".

With **the Net Zero Industry Act**, the Commission seeks to establish a regulatory environment to scale manufacturing capacity in the EU for the technologies that are deemed of 'strategic importance' for the Union.[39] This is done to simultaneously reach its climate targets and reduce supply chain dependencies. By combining policy measures such as shorter permitting deadlines for manufacturing sites, regulatory sandboxes[i] and a non-price criterion that takes into consideration the country of origin of the renewables components in auctions, the Commission aims for the EU to meet more of its deployment needs through domestic production capacity.

The Critical Raw Materials Act attempts to increase the resilience of supply chains for critical raw materials, primarily by boosting the EU's capacity to extract, process and recycle these materials.[40] The proposal sets domestic targets to be met by 2030 and identifies a list of critical raw materials required to manufacture the necessary technologies for the digital and green transitions. The Act acknowledges that domestic measures will not make the EU fully self-sufficient in critical raw materials, which is why the Commission has engaged in a strategy to diversify its imports. The EU is currently in talks with the United States about a 'critical raw materials club' for like-minded countries.

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[i] A regulatory sandbox is a tool allowing businesses to explore and experiment with new and innovative products, services or businesses under a regulator's supervision.

Higher geopolitical tension and interdependencies place stronger emphasis on local manufacturing and control of supply chains

Global and national fragmentation

We are in a period of major geopolitical, demographic, economic, and technological change. In 1995, the EU, US and Japan accounted for 70 per cent of global GDP. In 2021, this share was 49 per cent, while China's share has grown to 16 per cent of global GDP in current prices.[41] This change has a profound impact on the energy transition.

The period since the signing of the United Nations Framework Convention on Climate Change in 1992 until today has been characterised by globalisation, high global growth, and low inflation. Now we are entering a period in which, according to the World Bank, nearly all forces that powered growth and prosperity since the early 1990s have weakened.[42] We already see that increased geopolitical tension is challenging for the coordination of global climate action and increases the emphasis on security of supply and value-chain resilience.

At the national level, we also see increased fragmentation. Across Europe, populists – especially right-wing – have increased their electoral strength in recent elections, according to Pew Research Center.[43] In Italy and Hungary, populist right-wing parties are currently the controlling government, and Sweden, France, Netherlands, among others, have experienced a surge in populist support over the past decade. Despite being one of the few countries that has to some degree bucked this trend over the last elections, Germany's "Alternative für Deutschland" (AfD) party has also risen in popularity in recent polls, with opposition to government and EU climate policy as a main driver – which highlights the risks this entails for a concerted energy transition in the EU.[44]

Any transition will meet opposition, but if the effort to reduce greenhouse gas emissions impacts nations, vulnerable groups, or individuals in an unjust way, it will lose necessary support and traction. Several climate mitigation and adaptation actions have multiple synergies with UN's Sustainable Development Goals (SDGs) and sustainable development in general, but some actions may also mean trade-offs for both nature and people. There are no quick fixes for these trade-offs, but they can be minimised through the meaningful participation of local communities, indigenous peoples, and vulnerable populations. Achieving meaningful participation among the groups and regions that may lose out on the transition is key to ensuring the social cohesion needed for a rapid and deep transition.

This development underlines the need to keep the cost of the energy transition low, to both protect vulnerable consumers and ensure political support for action. According to the International Monetary Fund (IMF), many countries will move towards budget consolidation, reducing the space to create climate policies, such as subsidies.[45] Subsidies put a strain on public finances and impact the ability to compensate those who lose out from the energy transition. Solutions like carbon pricing can give a cost-efficient transition while strengthening public finances but run the risk of hitting vulnerable households disproportionately. To secure a sufficiently fast and efficient energy transition, while keeping sovereign debt at sustainable levels and retaining political support, a wide range of policy tools are necessary.

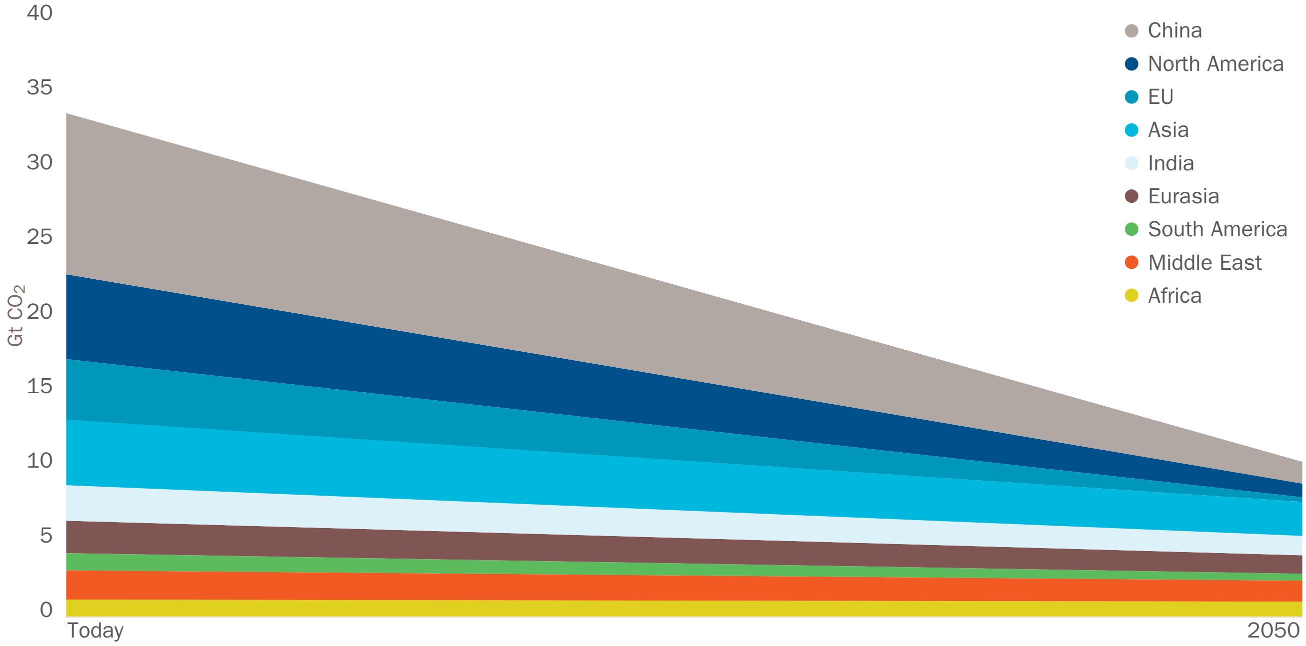
New policy objectives with uncertain impacts

Higher geopolitical tension and interdependencies place stronger emphasis on local manufacturing and control of supply chains. These priorities have so far led to increased economic support for renewable energy and manufacturing of renewable technology, both in the US and EU.[46]

It is still too early to judge the long term effect of subsidy-driven and more protectionist focused policies such as IRA and Net Zero Industry Act. So far, the emphasis has been on developing more resilient supply chains, but this has not led to a decoupling from global supply chains. Still, tariffs and less global co-operation could lead to higher costs for renewable technologies and slower technology transfer.

It is also important how the targets for more local content are reached. Investment in research and support for additional manufacturing capacity can spur innovation that leads to lower prices and more global public goods, thus accelerating the green transition in the long term. However, less global trade and collaboration could restrict the developing world's access to this innovation, thus increasing costs and slowing the energy transition.

6 Global energy-related CO_2 emissions ($GtCO_2$) by region from today to 2050 in the Low Emissions Scenario



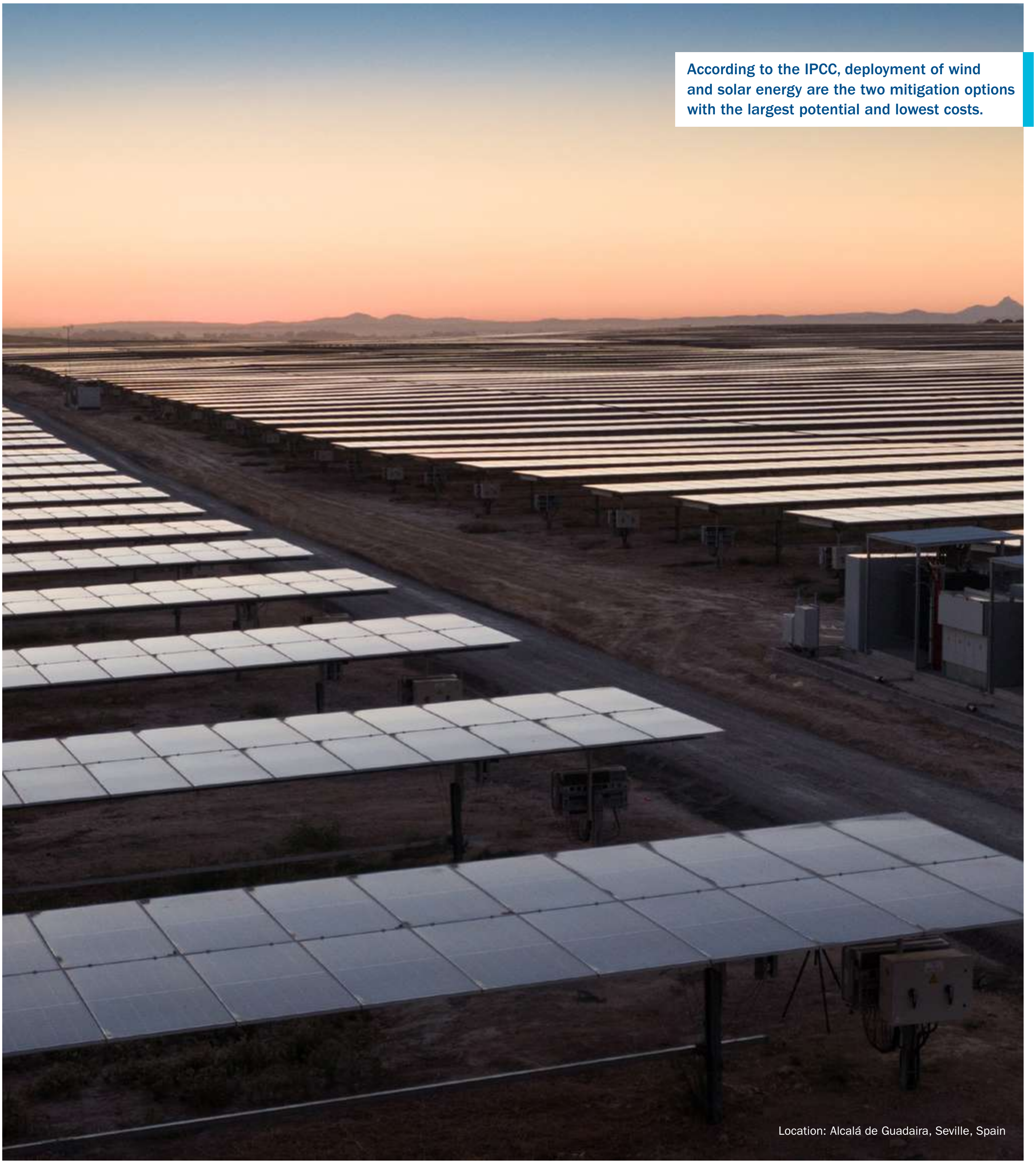
Urgent action needed to tackle the climate crisis while also ensuring sustainability in the broader context

In 2023, the synthesis report for IPCC's Sixth Assessment Report (AR6) was released. The report reiterates that human activities have caused global warming with global surface temperature reaching 1.1 degrees above 1850-1900 levels in 2011-2020. With the AR6, we can, with an even greater degree of certainty, attribute human activity to climate change, and the potential consequences of global warming are better understood. To limit global warming to 1.5 degrees without large overshoots, global emissions must be halved by 2030 and net zero must be achieved mid-century. According to the IPCC, deployment of wind and solar energy are the two mitigation options with the largest potential and lowest costs.[47]

As global temperatures have already increased and will continue to increase until global emissions reach net zero, IPCC emphasises the importance of adaptation to climate change. In Norway during the extreme weather event, Hans, hydropower's ability to mitigate flooding proved crucial in reducing what would have been a 1,000-year event to a 100-year flood instead, in some regions.[48] According to the World Meteorological Organisation, the extremes we have experienced in 2023 are the new norm, underlining the need for adaptation.[49]

While the energy transition is picking up pace in Europe, USA and China, other parts of the world are still lagging. The developing countries outside China represent the majority of the global population and most of global energy demand growth, but at the same time, less than 20 per cent of global clean energy investment.[50]
Our analysis finds that to keep global warming well below 2 degrees, it is key that developing countries also increase investments in renewable energy – especially as these countries are key drivers for economic and energy demand growth. Investments in fossil fuel-based solutions today risk locking in emissions long term.
In the Low Emissions Scenario, the developing world accounts for a substantially larger share of total global emissions in 2050 (Figure 6).

Proper financing is vital to achieve acceleration in deployment of clean energy technologies. At COP 27 in Sharm-El Sheik, climate financing was at the top of the agenda as developed countries were held accountable for not delivering the 100 billion dollars promised.[51]
At this year's COP in Dubai, financing will again be an important part of the discussion. This COP will be the first "Global Stocktake"[i] and provide a comprehensive assessment of progress since adopting the Paris Agreement. Ensuring that developing countries, especially the least developed, are able to take part in the energy transition is important to both ensure global development and deliver on the Paris Agreement targets.


According to the IPCC, deployment of wind and solar energy are the two mitigation options with the largest potential and lowest costs.

Location: Alcalá de Guadaira, Seville, Spain

In addition to the climate crisis, the world faces additional ecological challenges including the loss of ecosystems and biodiversity, as well as pollution.[52] In 2022, the 15th COP of the UN Convention on Biological Diversity marked the adoption of the Kunming-Montreal Global Biodiversity Framework.[53] This sets targets to be achieved by 2030, including 30 per cent conservation of land and sea, 30 per cent restoration of degraded ecosystems, halving the introduction of invasive species, and $500 billion/year reduction in harmful subsidies. In addition, the overarching goals to be achieved by 2050 include halting human-induced species extinction and unsustainable use of biomass. Increased emphasis on nature conservation and biodiversity protection will have consequences for the response to the climate crisis. Conservation of nature may have a positive effect on emissions from land use, but at the same time it may limit the area available for renewable development.

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[i] The global stocktake is a process for countries and stakeholders to see where they're collectively making progress towards meeting the goals of the Paris Climate Change Agreement – and where they're not. The stocktake takes place every five years, with the first-ever stocktake scheduled to conclude at the UN Climate Change Conference (COP28) . It links the implementation of nationally determined contributions (NDCs) with the overarching goals of the Paris Agreement, and has the aim of raising ambitions.

Markets, technology and policy reinforcement needed

As we will show in this Low Emissions Scenario, the development of sustainable and renewable energy, combined with energy efficiency and the electrification of end-use sectors, are the main pillars needed to navigate the energy transition. The climate crisis calls for urgent action and time is a major limiting resource. Over the past decades, public subsidies for renewable energy have led to falling costs. Several renewable technologies, including onshore wind, solar PV, and heat pumps, are now cost competitive with fossil alternatives and battery electric vehicles are close to cost parity. This creates a strong dynamic in which politics and markets work together to enable a rapid transition. At the same time, the speed must accelerate to reach 1.5 degrees, and for harder-to-abate sectors, the need for public support is still significant.

Statkraft has long been a strong proponent of carbon pricing as a core climate policy instrument. The government revenues created from this market may also be used to ensure a just transition. Recent empirical research shows that the harm of carbon pricing on economic growth is muted and that the macroeconomic cost of an efficient transition is relatively low, while a delayed and disorderly transition is more expensive.[54] Carbon pricing is key to facilitating a rapid and cost-efficient transition. This must be combined with subsidies and regulation to support innovation and scaling of new technologies.

The world faces increased uncertainty and higher degrees of tension versus just a few years ago. However, the Low Emissions Scenario shows that even in a scenario that assumes more conflict and protectionism, the energy transition continues at a relatively high pace. With the additional strengthening of policies and financing for renewable technologies in developing economies, the energy transition could accelerate and bring us closer to 1.5 degrees.

Over the past decades, public subsidies for renewable energy have led to falling costs

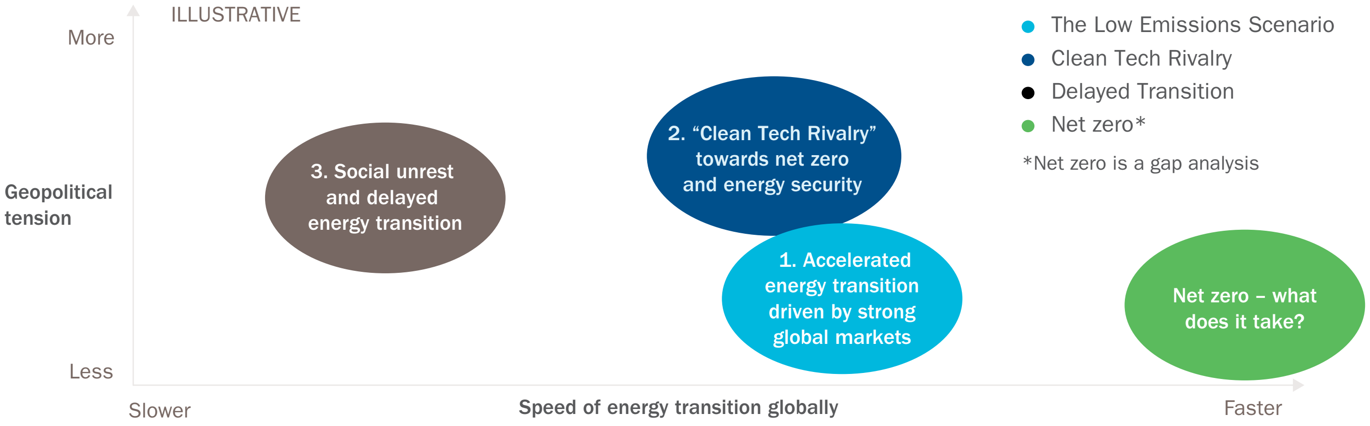
Several renewable technologies, including onshore wind, solar PV, and heat pumps, are now cost competitive with fossil alternatives and battery electric vehicles are close to cost parity.

CHAPTER 2

The energy transition in a fragmented world

Location: Baillie wind farm, Scotland

7 The speed of the energy transition and degree of geopolitical tension in the different scenarios towards 2050



As geopolitical uncertainty rises, we face choices that could significantly impact the worldwide shift towards cleaner energy. In the coming decades, energy systems must develop to meet climate targets while ensuring energy security. They need to follow a transition pathway that effectively utilises energy and financial resources, while also safeguarding vulnerable consumers and households.

In the Low Emissions Scenario, markets, policy, and technology work together, offering a pathway to substantial decarbonisation in a cost-effective manner. However, we also explore alternative scenarios in the Clean Tech Rivalry and Delayed Transition. These demonstrate how decisions on global and national issues could influence the long-term energy transition.

Statkraft's Low Emissions Scenario rests upon a foundation of well-functioning global markets and supply chains, proactive and efficient climate policies, and international collaboration, all of which drive advancements and cost reductions in clean technologies. However, as described in Chapter 1, the increased geopolitical tension and attention to energy security and affordable energy prices may affect the transition ahead.

In response to this growing uncertainty, we introduce two additional scenarios in this year's report. The first is the "Clean Tech Rivalry towards Net Zero," a scenario where global superpowers engage in a subsidies-driven competition for dominance in clean energy industries and supply chains. The second is the "Delayed Transition," which envisions a trajectory in which pressing near-term challenges such as rising living costs, social unrest, and security of supply concerns are higher on the political agenda.

These scenarios serve as windows into potential futures, offering insights into the potential outcomes of our decisions, policies, and actions.

While the new scenarios explore the challenges and consequences of alternative paths, our main scenario is the "Low Emissions Scenario." It is still a realistic but optimistic scenario, showcasing how collective efforts can lead to emission reductions at a low cost and a relatively high pace. In this scenario, technology breakthroughs, market dynamics, and proactive policies align to drive the clean energy transition forward.

Looking at the energy transition from three different perspectives provides insights into the interplay of geopolitical forces, policy decisions, technological advancements, societal priorities and economic development. The scenarios lead to different energy transition pathways, in areas such as renewable energy adoption, energy efficiency, technology choices, electrification and the decarbonisation of various sectors.

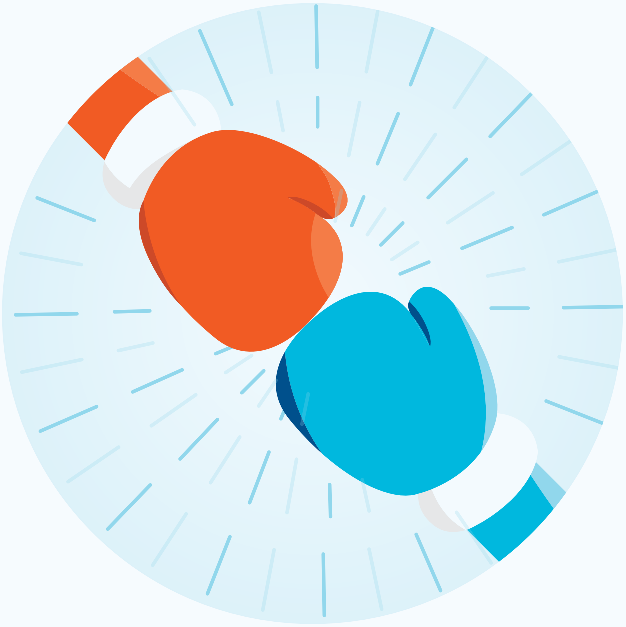
Statkraft scenarios

Our scenarios detail three different outlooks for the energy future towards 2050

1. Low Emissions Scenario

The **Low Emissions Scenario** is an optimistic, yet realistic scenario in which technology, market dynamics, and proactive policies accelerate the energy transition. Combined with global collaboration, this helps facilitate an efficient transition to cleaner energy sources, ensuring that emissions are reduced at a reasonable cost, supported by globally expanding carbon markets. Well-functioning global markets and supply chains enable robust economic growth, while market-driven technological advancements also help drive the clean energy transition.

China-EU/US relations are defined by agreed-upon rules and improved geopolitical stability, and a steady world economy creates an enabling environment for rapid progress. This scenario foresees the energy transition accelerating in developing nations as well, driven by both international pressure and the declining costs of clean energy technologies.



2. Clean Tech Rivalry Towards Net Zero

In the **Clean Tech Rivalry Towards Net Zero** scenario, the world's superpowers engage in a race for global dominance in the clean energy industries and to achieve net zero emissions – reminiscent of the "Space Race" between the Soviet Union and the US during the Cold War. Clean energy is seen as crucial for both energy security and cutting emissions. China, the US, and the EU become involved in a subsidy-fueled competition to develop clean industries and establish regional control over supply chains for renewable technologies. Increased emphasis on protecting local supply chains will reduce global trade in renewable technology, resulting in a more expensive and challenging energy transition.

Despite the push for clean energy, near-term emissions reduction targets face delays due to increased costs and the complexities of restructuring economies, industries, and supply chains. The subsidy race increases fear of carbon leakage from carbon prices, and in all markets other policy instruments are preferred. A subsidy-driven scenario leads to a more unpredictable transition, where state-led picking winners policies can lead to inefficient and more costly technology choices. In addition, a spending-based transition puts a significant strain on public finances. The higher cost of renewable technologies, coupled with limited investment and access to capital in developing countries, widens the gap between developed and developing countries.

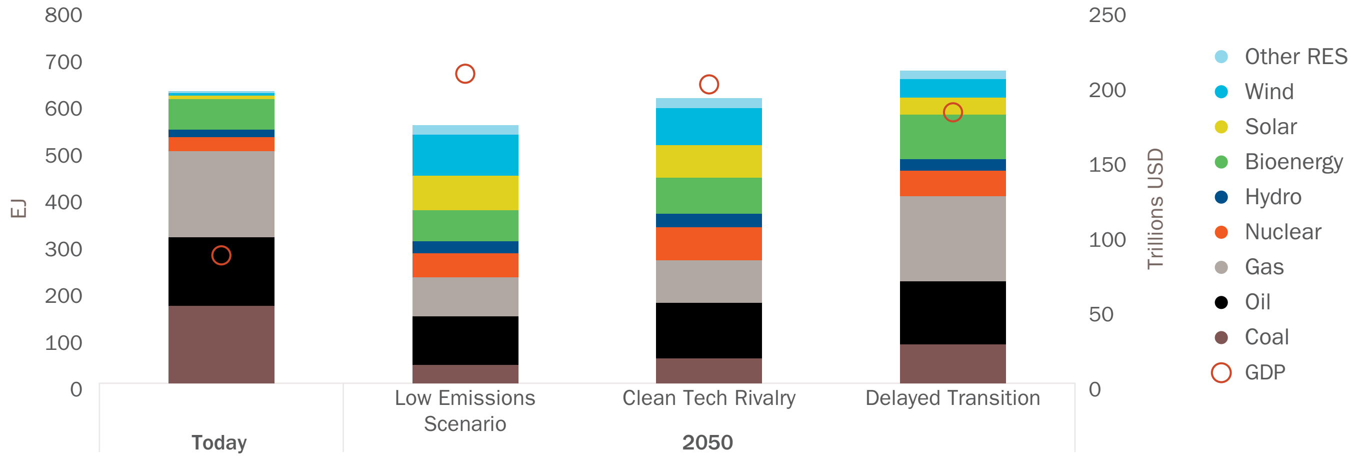
3. Delayed Transition

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 are driven by low cost, but the lack of policy drive makes it harder to reduce emissions in the end-use sector, especially the hard-to-abate sectors, and to remove costly residual emissions in the power sector.

Fossil fuel technologies with lower upfront costs emerge as a short-term solution for the energy crisis. The increased conflict and geopolitical tension make nuclear power not only important for energy security, but also strategic for national security reasons. Social unrest and political instability create uncertainty, and a slowdown in global economic growth. Protectionist policies become coping mechanisms for countries challenged by reduced standards of living. Emerging markets, hit by global economic downturn, struggle to keep pace with energy transition efforts.

Transforming fossil fuels, including coal, oil, and gas, into useful energy involves combustion, which leads to high energy losses in the form of heat

8 Global primary energy demand (EJ) and GDP (trillion 2021 USD)



Primary energy use declines to 2050 in the Low Emissions Scenario

Despite significant growth in the global economy and population, our analysis indicates a decrease in primary energy demand by 2050 as a result of electrification and other energy efficiency measures. The energy mix is expected to change considerably, with an increase in renewables and a decrease in emissions. However, this varies across scenarios. Scenarios with less energy efficiency and more energy-intensive growth result in higher energy primary energy consumption.

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

Transforming fossil fuels, including coal, oil, and gas, into useful energy involves combustion, which leads to high energy losses in the form of heat. In contrast, renewable power production is generated directly from variable, unlimited renewable sources and therefore requires fewer conversion steps and achieves higher efficiency.

Primary energy development in the Low Emissions Scenario follows a transformative path, anchored in three pillars: electrification, energy efficiency, and less energy-intensive growth.

Electrification: The scenario emphasises direct electricity use, reducing energy demand by replacing fossil fuels with efficient renewables in sectors such as buildings, transportation, and industries.

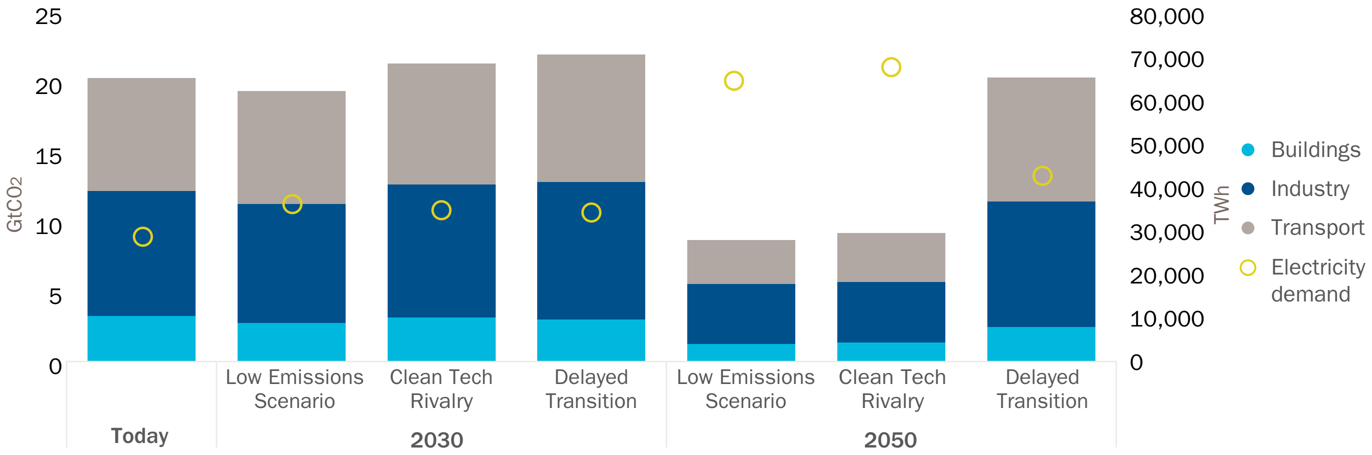
Energy Efficiency: Advances in technology, more efficient use of materials, recycling, and behaviour drive energy-efficient practices, reducing wastage and lowering overall energy demand across sectors.

Less Energy-Intensive Growth: Economic expansion shifts toward less energy-demanding sectors, aligning growth with reduced primary energy demand.

These pillars synergise to reshape primary energy development, fostering sustainability amidst economic progress. This development results in decreasing primary energy demand towards 2050, even with economic growth and an increasing population globally.

In the Clean Tech Rivalry and Delayed Transition scenario, progress across these three fronts diverges from the Low Emissions Scenario.

9 Global energy-related CO_2 emissions per sector ($GtCO_2$) and total power demand (TWh)



Electrification is the main climate solution

Energy efficiency, electricity, clean hydrogen, and bioenergy are keys in reducing emissions and dependence on fossil fuels in end-use sectors. The direct use of electricity, coupled with energy efficiency, is considered the most cost-effective approach where possible. However, the extent and speed of these changes vary across different scenarios. In the Clean Tech Rivalry scenario, short-term supply chain limitations and a less efficient, more costly transition result in higher emissions and increased demand. In the Delayed Transition scenario, less ambitious climate policies and slower technological progress leads to limited emissions-reductions in end-use sectors.

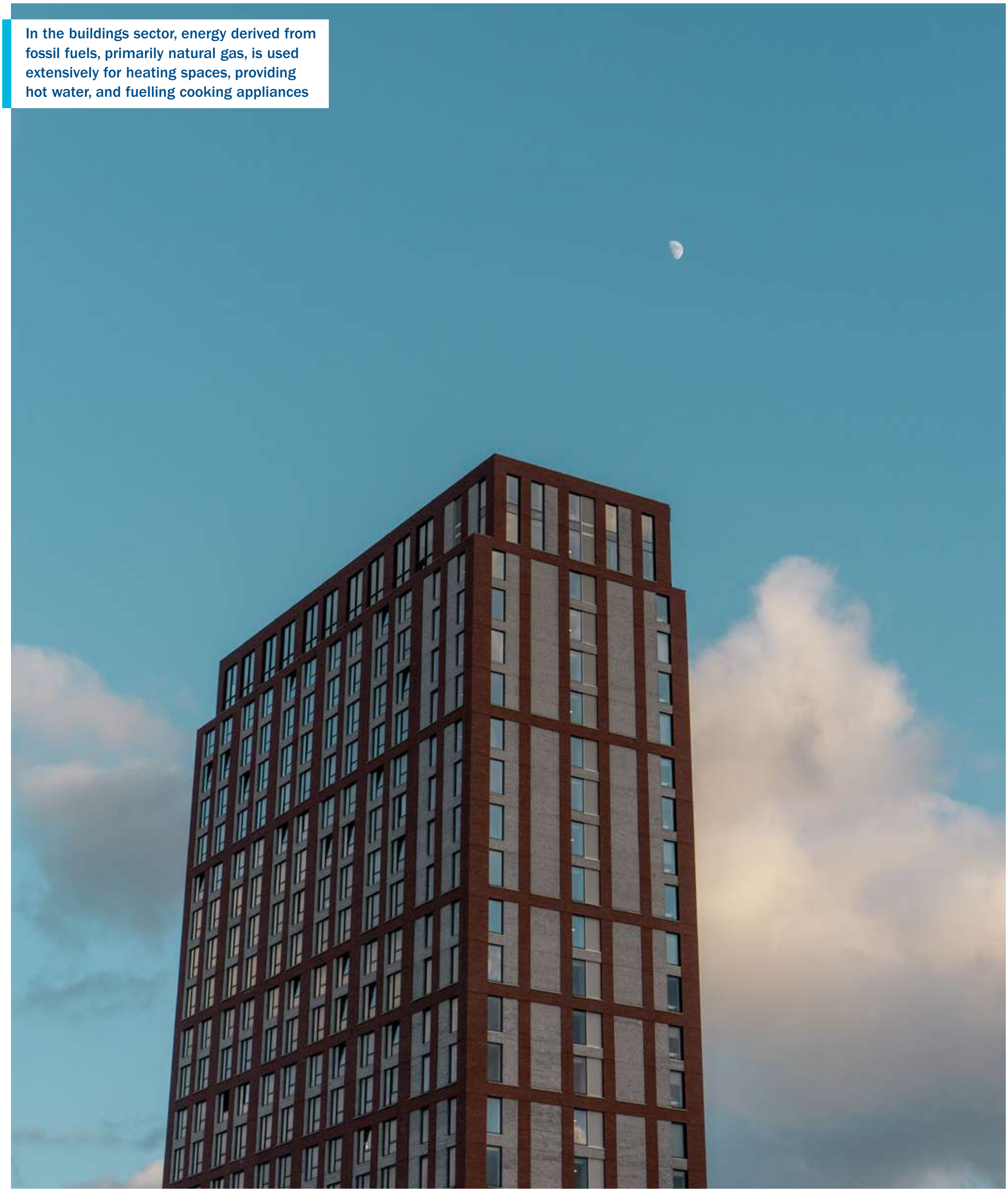
Presently, fossil fuels play a dominant role in covering the demand from end-use sectors. In the buildings sector, energy derived from fossil fuels, primarily natural gas, is used extensively for heating spaces, providing hot water, and fuelling cooking appliances. Similarly, the industrial sector relies on coal and natural gas for process heat, running machinery, and other manufacturing operations. These fossil fuels contribute significantly to the energy-intensive nature of industrial processes.

The transport sector heavily depends on liquid fossil fuels (primarily derived from oil) to power all means of transport. However, conventional internal combustion engines are relatively inefficient and contribute to global CO_2 emissions and local pollution.

The direct use of electricity combined with energy efficiency is deemed the most cost-efficient way of cutting emissions where feasible. With advancements in technology and reduced costs, electrification is gaining momentum in the transportation and buildings sectors, as traditional combustion engine vehicles are replaced with EVs, and fossil-fuelled boilers are replaced with heat pumps. Renewable energy sources are increasingly integrated in end-use sectors through direct use of electricity and green hydrogen, offering cleaner alternatives to fossil fuel-based energy. Coupling these sectors can provide much needed demand-side flexibility to the energy system as well. In addition to sustainable bioenergy, hydrogen will be an important energy carrier to reduce emissions in hard to abate sectors, such as high industry heat and long-haul transport where electrification is less feasible. Hydrogen is, however, far less efficient than direct use of electricity, and both hydrogen production and consumption are based on technologies that are less mature and require more policy push and technology development.

The shift from fossil to renewable electricity is essential to mitigate the environmental impact associated with fossil fuel use, paving the way for a more sustainable energy future. Electricity is an efficient energy carrier. It provides flexibility to the electricity system, it improves air quality, and it cuts emissions when sourced from renewables.

In the Low Emissions Scenario, global energy-related CO_2 emissions are reduced by around 50 per cent by 2050 (from 1990 levels), as the trends we see today continue and accelerate. With a focus on energy efficiency, increased electrification, and investments in clean hydrogen and bio energy, the world reduces emissions and its dependency on fossil fuels in the end-use sectors.

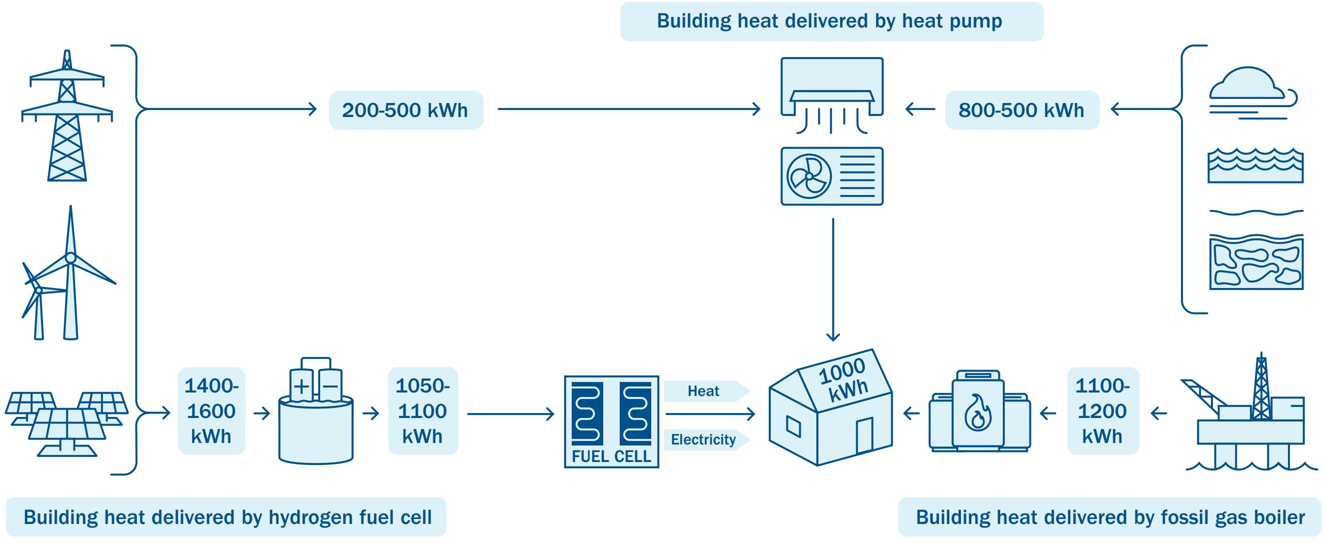


In the buildings sector, energy derived from fossil fuels, primarily natural gas, is used extensively for heating spaces, providing hot water, and fuelling cooking appliances

In the Clean Tech Rivalry, global emissions are reduced by around 40 per cent by 2050 (compared to 1990 levels). Costlier supply chains, inefficient policy instruments and insufficient investment in developing countries lead to a slower decarbonisation of the end-use sector towards 2030. However, as bottlenecks in the supply chain ease, electrification and hydrogen deployment accelerate towards 2050 and the deployment of renewables is 13 per cent higher than the Low Emissions Scenario between 2040 and 2050.

In the Delayed Transition, global emissions are approximately 25 per cent higher in 2050 (compared to 1990 levels). A lack of policy push, combined with a low carbon price, leads to the substantially slower decarbonisation of end-use sectors. Less deployment slows the technological development and delays cost reductions, making clean technologies less competitive. This delays emission reductions due to investments in fossil fuel technologies with lifetime of 20-40 years. The transition of the end-use sectors is far slower than in the Low Emissions Scenario and never catches up (Figure 9).

10 Energy needed to deliver 1000 kWh of heat based on hydrogen, heat pumps and fossil gas boilers



Decarbonising the buildings sector with heat pumps and energy efficiency

Currently, the buildings sector contributes to 30 per cent of global energy consumption and nearly 10 per cent of energy-related carbon emissions, but this share doubles if indirect emissions from electricity and heat production are included.[55] Energy use in buildings is primarily attributed to heating. In many regions, natural gas is commonly used for heating and cooking and in undeveloped countries, traditional biomass is typically used, underlining the importance of access to safe, clean, and sustainable energy.

Due to the growing emphasis on energy efficiency, energy consumption within the buildings sector remains at current levels towards 2050 **in the Low Emissions Scenario**, despite robust economic growth, population growth, and increased urbanisation in the developing world. However, the buildings sector's electricity consumption nearly doubles during this period, as electricity largely replaces coal, gas, oil, and traditional biomass. This shift contributes to a 63 per cent reduction in CO_2 emissions from present levels to 2050, and the share of electricity in the final energy demand increases from 34 to 63 per cent.

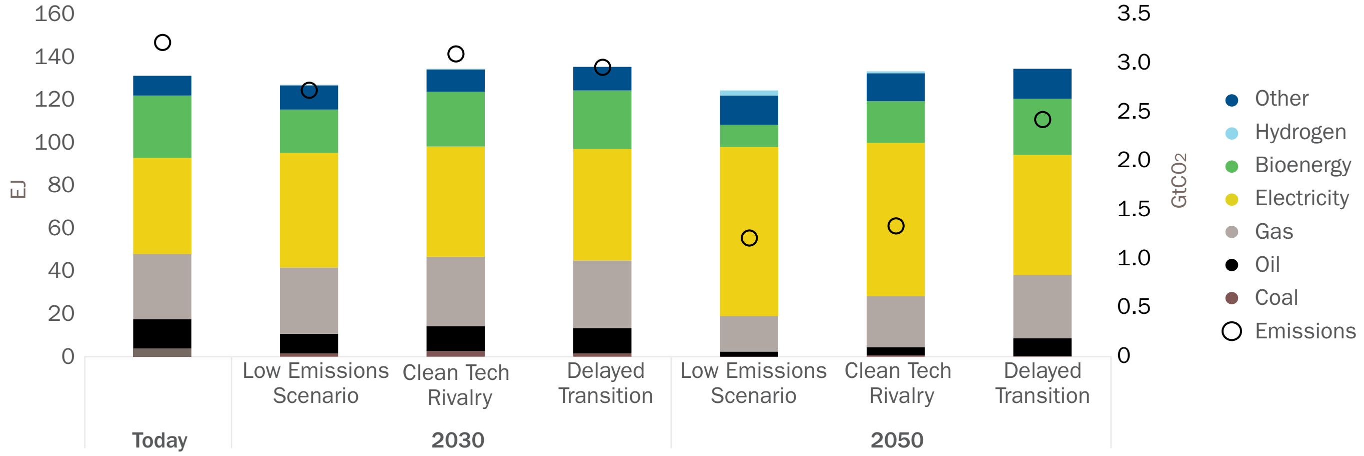
In the Clean Tech Rivalry and Delayed Transition scenarios, the required policy focus and investment in energy efficiency are lacking, leading to increased energy consumption. For the Clean Tech Rivalry, resources in developed countries are primarily allocated to clean energy supply, industries, and supply chain developments, leaving less funding for energy efficiency enhancements in buildings. The high upfront costs of energy efficiency lead to higher energy demand in both scenarios.
The lack of investments and robust policy framework for energy efficiency in new and existing buildings make it even harder for developing countries to reduce emissions (and energy demand) in the buildings sector, especially as the populations of developing countries grow and urbanise in tandem with economic growth. There will be a rapid increase in the need for floor space in these countries, which highlights the crucial role of robust policy frameworks to guide the energy transition in a sustainable manner.

This results in elevated energy demand from buildings by 2030, and the Clean Tech Rivalry and Delayed Transition surpass the Low Emissions Scenario by around 6 per cent and 7 per cent, respectively, in terms of buildings sector demand. Although electrification and energy efficiency gain momentum towards 2050 in the Clean Tech Rivalry, the Delayed Transition scenario fails to bridge the gap. Moreover, the proportion of electricity consumption is notably lower in the Delayed Transition, contributing to heightened emissions.

11 Ways to decarbonise the buildings sector color coded by cost of abatement
Blue: low cost of abatement; yellow: medium cost of abatement

Sub sector	Main solution		
Buildings	**Electrification**	**Heat pumps and direct use of electricity**	The most cost-effective way of shifting from fossil fuel-based heating systems is by direct electricity. Energy efficiency measures have a large cost range but is very necessary for reducing emissions in buildings.
	Energy efficiency		Heat pumps have a relative low energy-efficiency cost and are easy to implement in houses. They are very efficient due to their ability to extract heat from the air, water, or the soil, ultimately delivering more heat overall than through direct electricity, and when coupled with renewable energy sources, they can greatly reduce carbon footprints. Current models are 3-5 times more energy efficient than gas boilers (Figure 10).
		Passive design buildings	In new builds it is possible to incorporate passive design like strategic building orientation, natural ventilation, maximizing daylight can minimize the need for artificial cooling and lighting.
		Efficient appliances	Efficient appliances, LED lighting, and smart thermostats also play a crucial role in lowering energy use.
		Retrofitting existing buildings	Retrofitting existing buildings and reducing energy for heating through better insulation of walls and windows can significantly reduce energy consumption, but is usually more expensive with higher upfront cost and needs more planning.
	Behavioural changes		Changing habits like turning off lights and altering the accepted comfort temperature inside and adjusting thermostats can collectively make a significant impact.
	Renewable Energy Integration	**Rooftop solar**	Installing solar panels on rooftops and utilising solar energy for electricity generation can help buildings become more self-sufficient in terms of energy needs and reduce reliance on grid-supplied energy.
	District Heating and Cooling		Implementing district heating and cooling systems that use centralised sources to provide heating and cooling to multiple buildings can enhance energy efficiency and reduce emissions.
	Hydrogen		Clean hydrogen is a less efficient decarbonisation measure in buildings, and the uptake is expected to be limited. Hydrogen can be a niche solution in areas where the grid infrastructure is weak or where existing gas infrastructure can be reused for hydrogen.

12 Final energy consumption (EJ) and emissions (GtCO2) in the building sector



13 Ways to decarbonise the transport sector – color coded by cost of abatement
Blue: low cost of abatement; yellow: medium cost of abatement; red: high cost of abatement

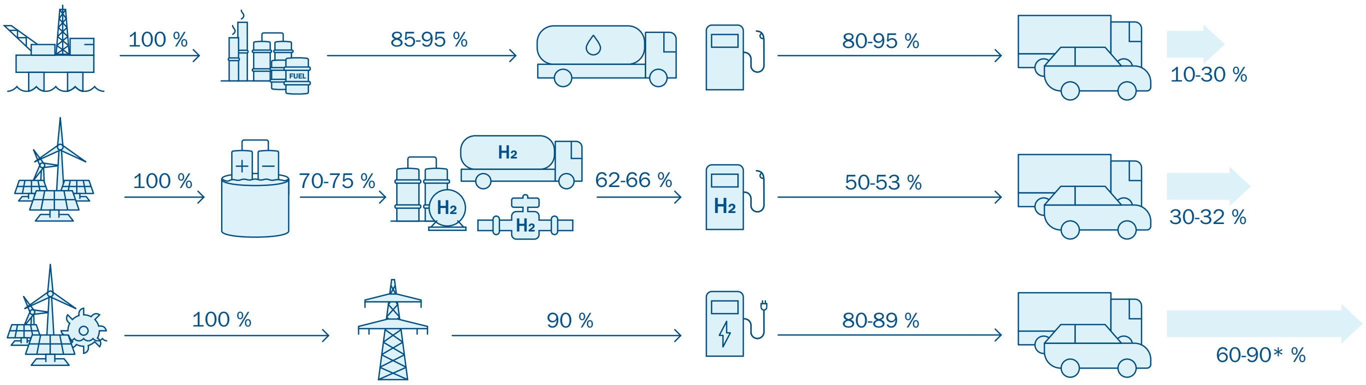
Sub sector	Main solution	
Passenger vehicles	**Electric vehicles (EV)**	A transition from internal combustion engine vehicles to electric vehicles (EVs) holds immense potential for reducing both CO_2 emissions and energy use. EVs produce zero tail pipe emissions and are more energy-efficient compared to traditional gasoline or diesel vehicles, as an electric car only uses around one-third of the energy of a traditional internal combustion engine (Figure 14).
Commercial transport	**Hydrogen (ammonia and synthetic fuel)**	Commercial vehicles and long-hall transport need biofuel, hydrogen, ammonia, and synthetic fuels to reach the required emission targets, as batteries are not sufficiently energy-dense to handle the long distance.
	Biofuels	
	Electric trucks	For shorter distances electric trucks are viable.
Aviation	**Hydrogen derived synthethic fuels (E-fuels) and biofuels**	Batteries are not sufficiently energy-dense for long distances, so hydrogen derived synthetic fuels are the main solution.
	Electricity	Electrification of local and regional routes are viable.
Shipping	**Emission-free ammonia**	For long distances, ammonia is needed.
	Electrification and hydrogen	Electrification of local and regional routes are viable.

Decarbonising the transport sector with electricity and hydrogen

The transport sector relies heavily on fossil fuels and is a significant contributor to global energy consumption and CO_2 emissions. It is responsible for approximately 23 per cent of global energy-related CO_2 emissions today, with road transport accounting for three-quarters of transport emissions.[56] The remaining transport emissions are from shipping, aviation, and rail.

In the Low Emissions Scenario, the global passenger vehicle fleet is all-electric in 2050, with a small share of hydrogen electric cars. A car has an expected lifetime of around 15 years, which means that the turnover of current passenger vehicles to EVs will take time, developing in parallel with rising EV sales and falling costs of EVs versus conventional cars in the coming years. Long-haul transport is expected to be a mix of electric and hybrid-fuelled trucks, bio-blends, and some fossil gas. All transport segments will become more efficient and will require less energy to transport the same goods

14 Energy losses for battery electric vehicle (EV), hydrogen fuel cell vehicle (HFCV) and internal combustion engine (ICE)



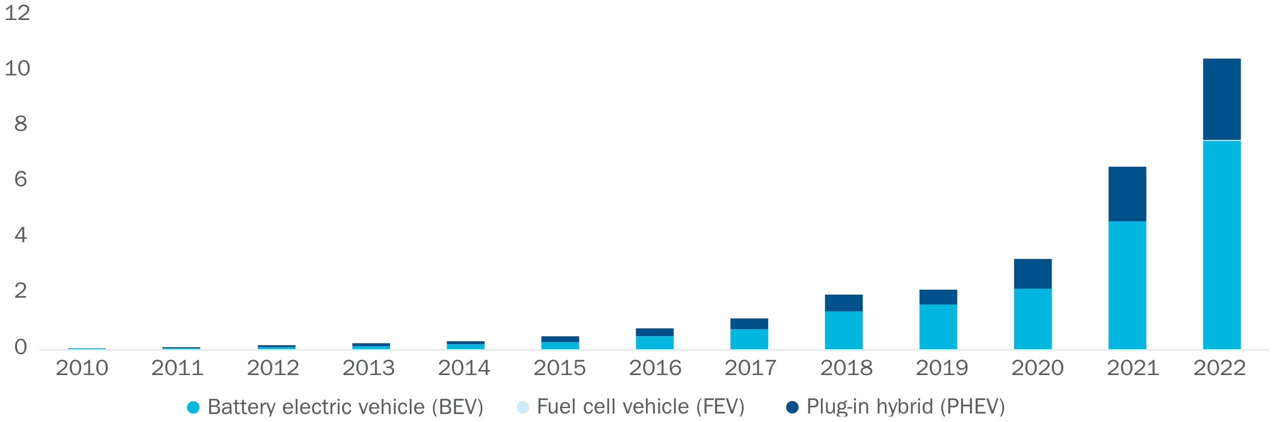
*lower end is without recovering mode on the electric cars

FACT BOX

Positive trends for deployment of electric vehicles

15

Global yearly sale of electric vehicles (million) (2010 - 2022)[57]



The sales of electric vehicles (EVs) are undergoing exponential growth, with more than 10 million units sold in 2022 alone (Figure 15). Notably, electric cars accounted for 14 per cent of all new car sales in the same year. China stands out as a major contributor, responsible for approximately 60 per cent of global EV sales, and accounting for more than half of the world's electric cars.

This trend has carried over into 2023, with about 5.6 million EVs sold in the first half of the year — an impressive 35 per cent increase compared to the previous year's figures.[58] Several key drivers are propelling this remarkable expansion:

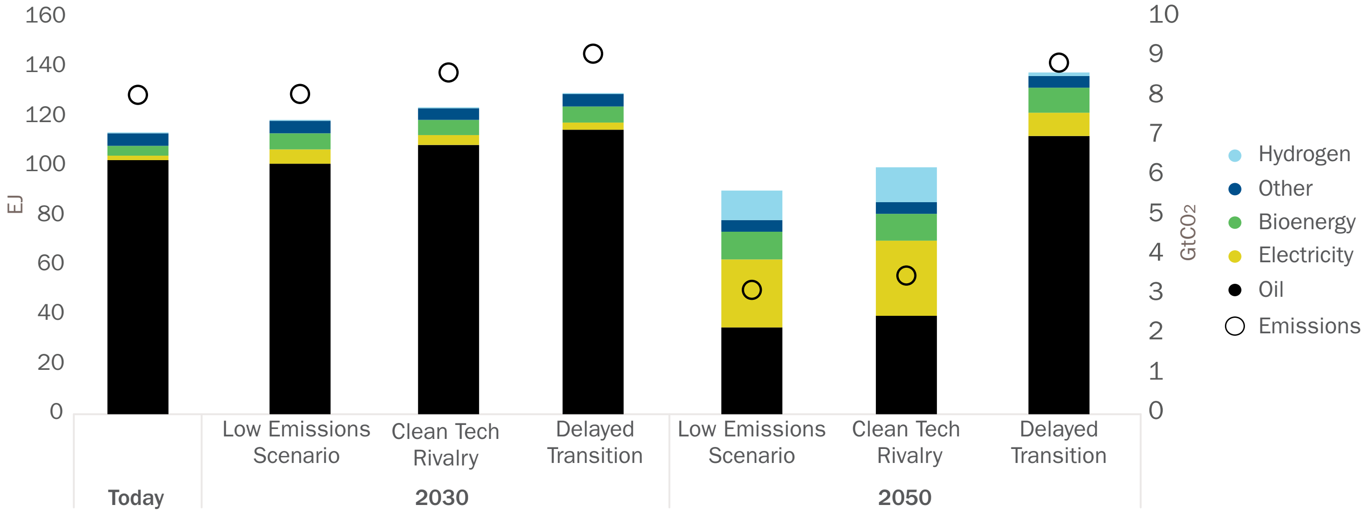
- Despite rising battery costs, EVs are becoming increasingly competitive compared to conventional vehicles.
- Government subsidies continue to play a role. However, only about 10 per cent of global spending can be attributed to government support. China, Norway, the UK, and various EU countries have reduced their subsidies.
- The electric car market has become highly competitive, with new Chinese companies offering more affordable models.
- Consumers now have a wider selection of models to choose from, including SUVs and larger vehicles (traditionally high in fuel consumption), which make up around 60 per cent of available battery electric vehicle (BEV) models in China and Europe.
- Supportive policies for charging infrastructure development are fostering further growth.
- Battery manufacturing capacity is expanding, reaching levels consistent with the 2030 emissions goals.
- Regulatory measures like the EU Fit-for-55 and USA's IRA policies are expected to boost growth through stricter CO_2 emissions and fuel economy regulations. Countries are striving to secure prominent roles in EV supply chains, exemplified by the Net Zero Industry Act in the EU, the IRA in the US, and India's emphasis on bolstering domestic EV and battery manufacturing.

While the EV supply chain is expanding, manufacturing remains concentrated in specific regions, with China leading the way in battery and EV component trade. Additionally, EV growth is concentrated in advanced economies and China, leaving the rest of the world trailing behind.[59] Emerging and developing economies face hurdles in EV adoption due to a lack of fiscal incentives, inadequate infrastructure, and high prices.

Subsidies have played a pivotal role in driving the adoption of EVs across various countries worldwide. This strategic approach has propelled China to take the lead in EV production, with a production of almost 6.5 million EVs and plug-in hybrids in 2022.[60] However, this triumph has not been achieved without its own set of challenges.

As China strategically developed its EV industry over the past decade, the subsidies triggered an unintended consequence – an excess production of EVs. [61] Initially embraced by ride-hailing companies, these vehicles swiftly became obsolete as a result of rapid technological advancements in battery range. This has led to an accumulation of unused EVs within some of China's largest urban centres, which serves as a poignant illustration of one of the potential drawbacks associated with a transition driven primarily by subsidies.

16 Final energy consumption (EJ) and emissions ($GtCO_2$) in the transport sector



and people, while the underlying demand for mobility is expected to grow. In the Low Emissions Scenario, emission-free ammonia appears to become a key solution for long distance maritime freight towards 2050, while e-fuels, such as e-methanol, play a key role in aviation. For both shipping and the aviation sector, shorter local and regional routes can be electrified.

In the Clean Tech Rivalry, reduced global trade and the restructuring of global supply chains for emission-free vehicles lead to cost increases and delayed targets. This results in more muted electrification globally. However, as the world solves bottlenecks with regards to regional supply chains, growth accelerates substantially starting around 2030. The nature of the subsidy-driven transition will lead to a less efficient transport sector with higher energy and electricity demand compared to the Low Emissions Scenario. Even so, the electrification of transport is roughly the same by 2050 as in the Low Emission Scenario.

In the Delayed Transition, EV subsidies are reduced substantially as resources are shifted to protect consumers from higher fuel prices, and the lack of government support and infrastructure for emission-free solutions (for long-haul transport, shipping, and aviation) keeps emissions in the transport sector at a high level. As governments face increased tensions both globally and domestically, decarbonisation targets are postponed. And when combined with increased cost of living, the result is a slower replacement of the existing, less efficient transport fleet, thus locking in emissions for longer and sparking higher energy demand. Low or no prices on carbon emissions and the lack of other policies result in fewer cost reductions for non-mature technologies, making the transition for shipping and aviation hard to achieve.

Decarbonising the industry sector

The industrial sector plays a crucial role in global energy consumption and carbon emissions. The industry sector is energy- and emission-intensive, consuming 38 per cent of the world's energy and accounting for about 27 per cent of energy-related CO_2 emissions globally.[62] This is primarily from manufacturing, processing, and other production activities. It relies heavily on fossil fuels, such as coal, oil, and natural gas for heat, power, and feedstock.

Industries such as steel, cement, and chemicals require high-temperature processes that often rely on fossil fuels, leading to substantial CO_2 emissions. These processes are hard-to-abate, meaning that they are challenging to decarbonise through direct use of electricity because they require higher temperatures than electricity can deliver.

Even though there are solutions, the road to decarbonisation in these energy-intensive industries is not without challenges. Many of the necessary technologies are still in the prototype or demonstration phase, necessitating further development before large-scale deployment. Additionally, several of these innovative production processes come with higher costs. Given the fiercely competitive nature of global markets for heavy industry products like steel, the tight profit margins make absorbing substantial production cost increases challenging. Furthermore, industrial facilities are capital-intensive and have expected lifetimes of around 40 years, which complicates rapid transformation.

Considering these complexities, decarbonising the industry sector requires a comprehensive toolbox of solutions. Balancing technological innovation, policy support, and market incentives becomes essential to enable the transition towards a more sustainable and low-carbon industrial landscape.

17 Ways to decarbonise the industry sector color coded by cost of abatement
Blue: low cost of abatement; yellow: medium cost of abatement; red: high cost of abatement

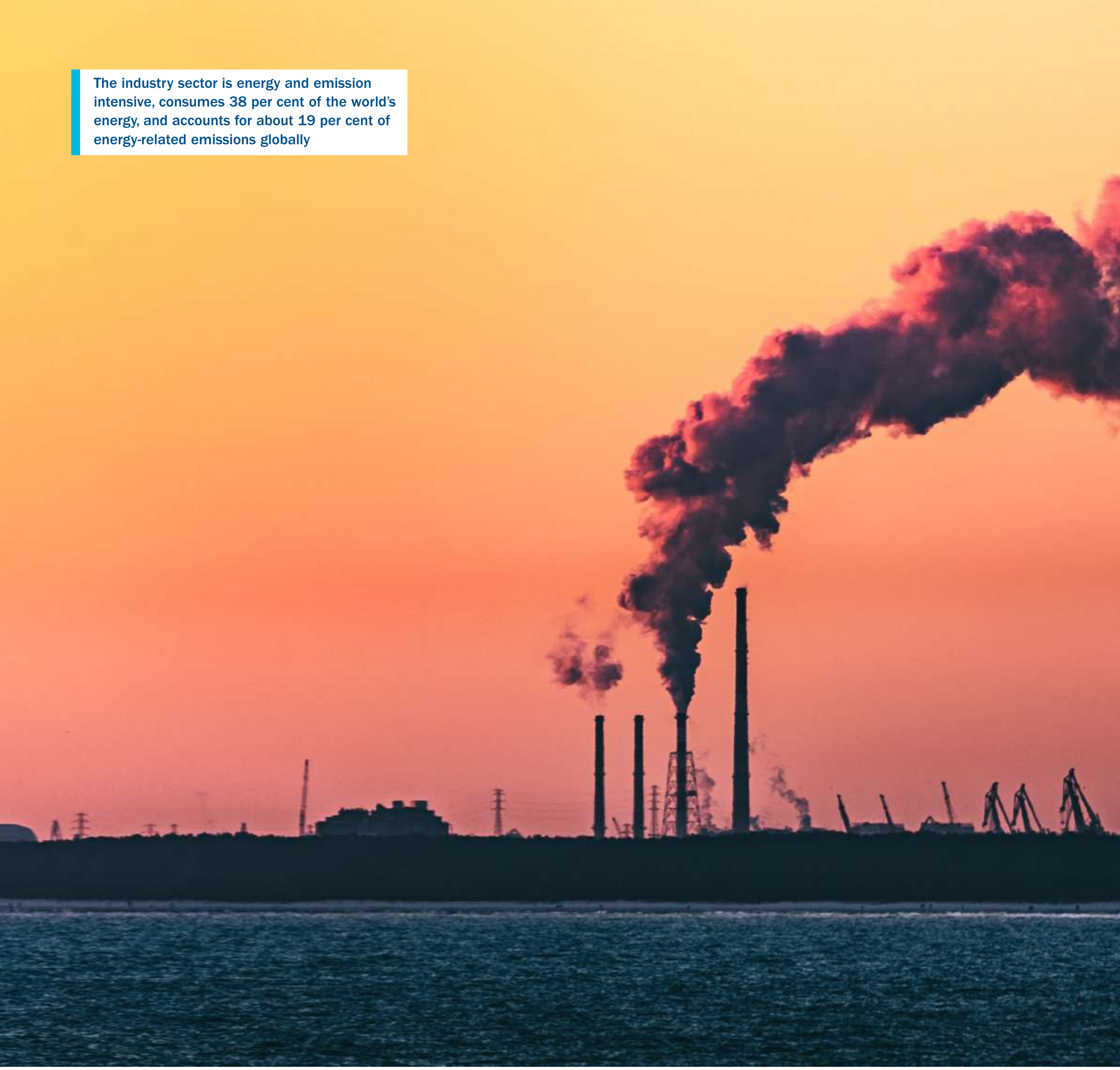
Sub sector	Main solution	
Low-temp. industry	**Electricity**	Industry with temperature requirements under 200°C are far less energy intensive and can be decarbonised with electrification.
Petro-chemicals	**Bio based**	The petrochemical industry uses fossil fuels as feedstock to produce chemicals and materials such as plastics, fertilizers, clothing, cosmetics, etc. The sector requires alternatives such as bio-based or low-carbon hydrogen feedstocks for chemical and material production.
	Hydrogen	
Chemicals	**Hydrogen**	Emission-free hydrogen can be used in ammonia production. CCUS will be key to decarbonise chemical production.
	CCUS	
Iron and steel	**Hydrogen**	Replacing coal and fossil gas with emission-free hydrogen.
Cement	**CCUS**	Shift from coal to sustainable bioenergy and/or implementing CCUS technologies to curtail the emissions from clinker production.
	Bioenergy	
Industry-wide	**Recycling**	Recycling, as well as material and energy efficiency are the most cost-efficient ways to reduce energy related emissions and energy consumption in industry. Recycling is well established within metals, plastic, glass, and paper, but needs scale. Lifetime extensions of buildings, improved design, and manufacturing techniques, along with light weighting can help reduce emissions.
	Material efficiency	

In the Low Emissions Scenario, the industrial sector's energy consumption in 2050 is somewhat lower than today, despite economic growth, and the sector sees a 50 per cent reduction in energy-related CO_2 emissions by 2050 compared to the present. This outcome arises from improved energy efficiency and recycling, electrification, the adoption of emission-free hydrogen, and some implementation of Carbon Capture, Utilisation, and Storage (CCUS).

The global process of electrifying industries will be a gradual one, and the Low Emissions Scenario envisions a steady transition towards 2050. Approximately 38 per cent of the industry's global energy demand will be met by direct electricity consumption by 2050. Clean hydrogen contributes significantly to industry decarbonisation and will cover almost 11 per cent of the industry's energy demand by 2050. This transition will replace the use of fossil gas and coal for chemical feedstock, steel production, and other high-temperature heat applications.

In the Clean Tech Rivalry, the US, EU, and China establish new clean industries and robust supply chains leading to increased industrial activity, while simultaneously decarbonising existing industries and maintaining cost competitiveness. This is complicated by the slower expansion of renewable energy sources, which delays the rollout of green hydrogen, despite substantial subsidies to support it. Supporting technologies with subsidies rather than through carbon pricing leads to less efficient solutions and undermines material and energy efficiency. Developing nations invest in fossil fuel technologies to propel their industrial growth, thus increasing emissions.

The industry sector is energy and emission intensive, consumes 38 per cent of the world's energy, and accounts for about 19 per cent of energy-related emissions globally

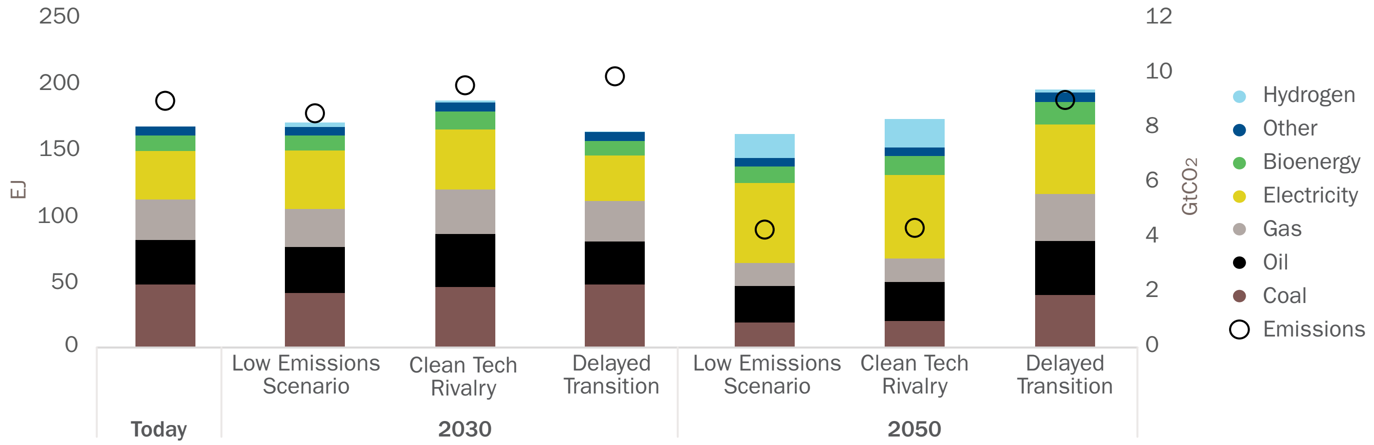


This results in higher energy demand and more emissions from industry, compared to the Low Emissions Scenario, especially before 2035. The transition trajectory regains momentum towards 2040 and 2050, as supply chain issues are resolved. More efficient technology and recycling reduce energy demand, but not to the levels of the Low Emissions Scenario. Electricity and hydrogen deployment accelerate, covering 37 and 12 per cent of demand in 2050, respectively.

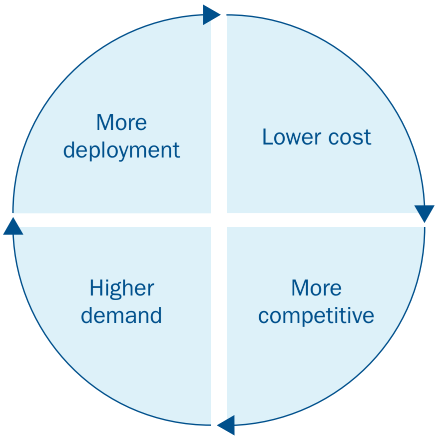
For the Delayed Transition, reduced global trade contributes to a decline in economic growth, while protectionist policies steer the trajectory towards more nationalised industries. Climate policies and the advancement of technologies for industry decarbonisation are given a lower priority, overshadowed by the emphasis on shielding consumers from escalated living costs and safeguarding pivotal industries. The consequence of this is continued operations of existing industrial plants and the establishment of new fossil-fuel-based facilities. The muted emphasis on material and energy efficiency results in less effective and innovative industrial processes.

This leads to heightened demand and emissions from the industrial sector, 11 per cent and 109 per cent higher than the Low Emission Scenario, respectively. The lack of technological development leads to little deployment of CCUS and hydrogen, resulting in elevated emissions level throughout the time horizon.

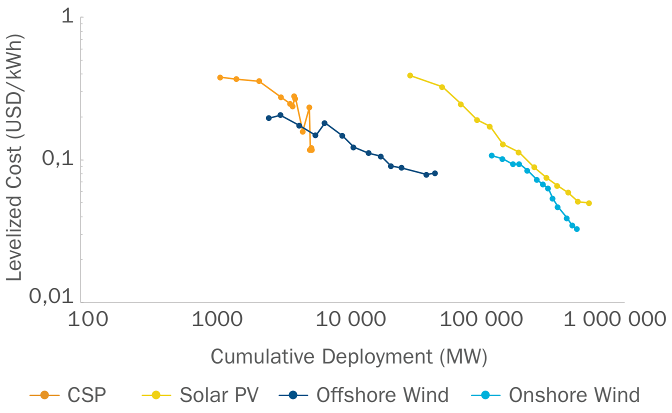
18 Final energy consumption (EJ) and emissions ($GtCO_2$) in the Transport sector



19 Virtuous cycle of renewable energy deployment



20 Learning effects reduce cost of renewable energy sources, 2010-2022[64]



Competitive renewables drive the energy transition

In the Low Emissions Scenario, power consumption is projected to more than double to 2050, with 82 per cent of this demand being met by renewable sources. Solar PV emerges as the dominant power generation technology, seeing a 22-fold increase from today's levels. Onshore wind and offshore wind also grow exceptionally. Across all scenarios, emissions are reduced as cost-effective wind and solar power replace fossil fuels in power generation.

The world needs vast amounts of renewable power to reduce emissions in all end-use sectors. Extensive electrification, both direct and indirect through the deployment of green hydrogen, must start in parallel to the decarbonisation of the power sector. In addition, more than 760 million people still lacked access to electricity worldwide in 2022, hindering economic growth and development.[63] Decarbonising power generation while supplying the electricity needed in the future is a major challenge, but technologically and economically feasible.

Fortunately, renewable energy sources have experienced unparalleled cost decline over the last decades.
The cost of onshore wind and solar power have gone down by 69 per cent and 87 per cent, respectively, since 2010 (Figure 20), and the generation capacity has grown accordingly, as these cost reductions and climate policies have reinforced each other. Climate policies have helped drive down the cost of renewable energy and cheaper renewable energy has reduced the cost of achieving climate targets. As a result, solar and wind are, to an increasing extent, outcompeting fossil fuel technologies, not only new fossil fuel plants, but also existing ones.

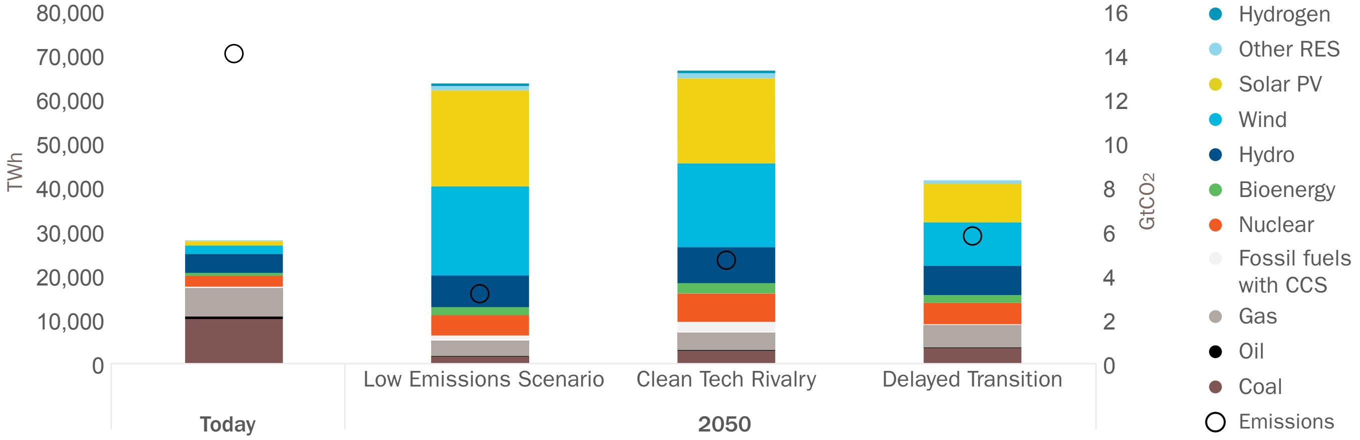
Renewables replace fossil energy in all scenarios, but at different speeds

Due to wind and solar power cost competitiveness, the shift from fossil fuels to renewables in power generation continues in all our scenarios. The magnitude and speed of electrification of end-use sectors, however, vary substantially.

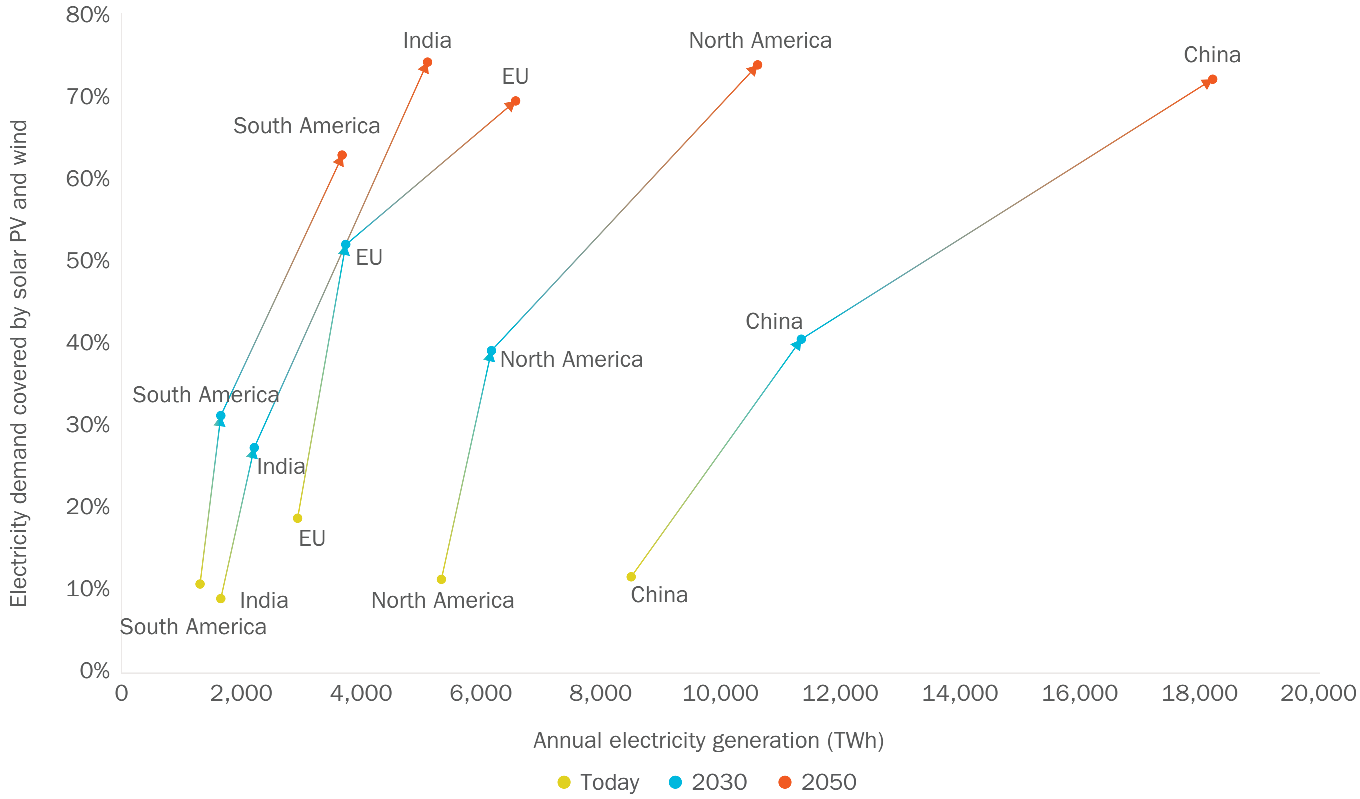
In the Low Emissions Scenario, power consumption more than doubles from 2021 levels to 2050 (Figure 21). Solar and wind power will provide most of the new power generation needed to cover this demand, while simultaneously replacing existing fossil fuel generation. In some countries and regions, the share of wind and solar will cover more than 70 per cent of electricity demand in 2050 (Figure 22). In 2050, 82 per cent of global power generation stems from either solar, wind, bioenergy, hydro, or other renewables, leading to a 77 per cent decrease in power sector CO_2 emissions compared to 2021 levels.

In the Clean Tech Rivalry scenario, the energy transition is driven by competition for dominance of renewable supply chains. Following the development of new value chains and a lack of global unity, costs will increase in the near term. This dampens the momentum of emissions reduction efforts, causing a decelerated and more financially demanding trajectory compared to the Low Emissions Scenario. As politically steered subsidies direct green investments in this scenario, instead of market-oriented policies like a carbon price, deployed technologies might not always be the most effective ones. This could lead to more expensive methods for decarbonising the power sector, such as nuclear and Carbon Capture, Utilisation and Storage (CCUS).

21 Power generation (TWh) by technology and annual power sector emissions (GtCO2) in 2050 for the transition scenarios



22 Regional electricity demand supplied by solar PV and wind in the Low Emissions Scenario



Also, overall energy efficiency will be lower, particularly in the transport and industry sectors, leading to a higher total power demand compared to the Low Emissions Scenario. The prevalence of fossil-based generation remains higher due to the slower integration of renewable sources, especially in the developing countries. The 2050 renewable generation share is 76 per cent in the Clean Tech Rivalry scenario, 7 percentage points lower than the Low Emissions Scenario.

In the Delayed Transition scenario, higher geopolitical uncertainty, more protectionism and increasing poverty hinders the energy transition. With focus on economic growth and energy security instead of sustainable climate action, use of fossil fuels remains prevalent in both power and end-use sectors. With less electrification, the overall power demand stays much lower than in the Low Emissions and Clean Tech Rivalry scenarios, but renewable energy sources will still represent two-thirds of the power mix by 2050, due to their cost competitiveness even in the Delayed Transition scenario. Wind and solar generation grow over 6.5 times (2021 - 2050), illustrating how falling costs for solar, onshore wind and batteries have put momentum behind the energy transition that endures, even in a case in which climate policies are weakened. This results in substantially lower power sector emissions even in this scenario.

Solar power is the global frontrunner in the Low Emissions Scenario

Location: Emmen, Netherlands

Solar PV is a winner in all scenarios

Power generation from photovoltaic solar panels is a very established technology that even decades after its invention still sees rapid technological development, both in terms of efficiency gains and cost reductions. Among the renewable energy sources, solar PV has the shortest building time. Further benefits of solar include its predictable production profile. This reduces system costs compared to wind power generation, although it increases the need for battery storage, grid expansion and seasonal storage.

Solar power is the global frontrunner in the **Low Emissions Scenario**. In a world characterised by international trade and scientific exchange, it benefits from well-developed, global supply chains and sees further technological advancement and cost reduction. This sets solar PV up for massive growth in the Low Emissions Scenario – with a 22-fold surge reaching the impressive threshold of 22,000 TWh electricity produced annually by the year 2050.

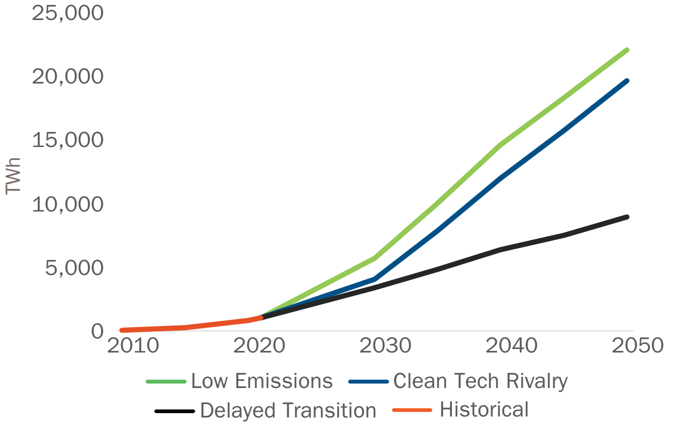
In the **Clean Tech Rivalry** scenario, the global solar PV deployment rate is similar to the Low Emissions Scenario post-2030. But the cumulative solar PV capacity lags behind the Low Emissions Scenario because of less building activity in the 2020s, when regional supply chains still need to be established.

Conversely, the **Delayed Transition** scenario lacks this solar boom. The absence of a climate push leads to much lower power demand, contributing to lower solar capacity growth. Still, favourable generation costs lead to an almost ninefold increase in solar power generation by 2050, compared to today's level.

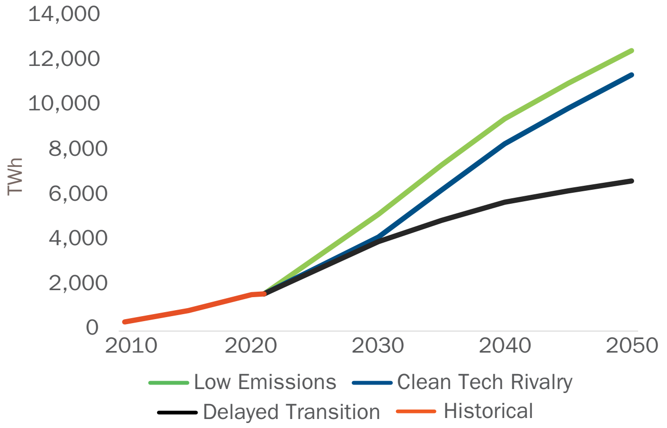
Onshore wind is the most cost-effective energy source in many regions

Onshore wind is another major frontrunner in the global power sector and stands out as the most cost-effective energy source in numerous regions. We predict an eight-fold increase in onshore wind power generation, reaching nearly 12,500 TWh by 2050 under the **Low Emissions Scenario**, enabled by increasing turbine size and higher investments. However, expansion faces land and grid challenges (see **Focus Grid**) in addition to local resistance. Multiple initiatives are already emerging with the aim of addressing these challenges, like designated "go-to" areas for renewable energy through EU's REPower Plan.[65]

23 Development of electricity production from solar PV (TWh) in the three scenarios.



24 Development of electricity production from onshore wind power (TWh) in the three scenarios



The wind power generation attained in the **Clean Tech Rivalry** scenario closely resembles that of the Low Emissions Scenario after 2030, with slower buildout in the 2020s. Compared to solar PV, however, the lag is less pronounced, primarily because the current supply chain for onshore wind is less concentrated than the solar PV supply chain.

In the **Delayed Transition** scenario, onshore wind generation does not increase as much as in the other two scenarios because of lack of policy support and lower electricity demand. But due to its low cost, power generation from onshore wind farms still sees a more than fourfold increase from today's level.

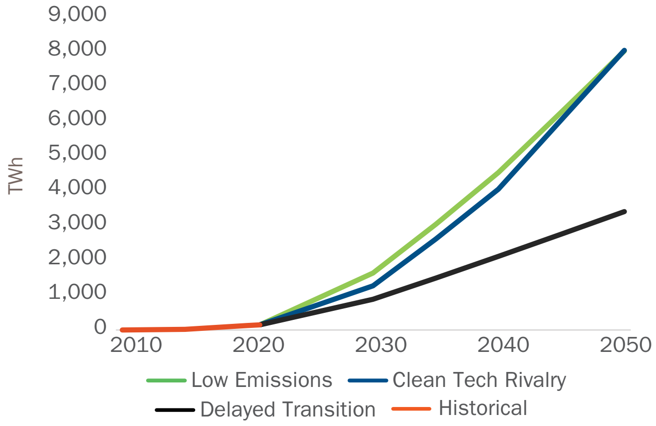
Offshore wind growth accelerates in 2030s – most affected by delayed transition

Compared to onshore wind, offshore wind power is a less mature technology. As of today, the necessity to base offshore wind turbines on the seafloor limits its buildout potential. Starting at the end of the 2020s, however, technological breakthroughs in floating offshore windfarms enable steep growth in the **Low Emissions Scenario**. Hence, it is not until 2040 that offshore wind experiences growth similar to the growth rates onshore wind and solar power exhibited in the 2020s. Still, offshore wind power production reaches 8,000 TWh annually in 2050, compared to 12,400 TWh from onshore wind, but from a much lower starting point in 2021 (144 TWh vs 1590 TWh).

Hampered by constricted technological exchange between geopolitical blocks and a fight for critical raw materials, offshore wind picks up later in the **Clean Tech Rivalry** scenario, only to catch up with the Low Emissions Scenario by 2050.

Lacking the necessary support schemes, the technological development and cost reductions are much slower, and offshore wind does not experience an accelerated deployment in the **Delayed Transition** scenario, reaching only 3,400 TWh of annual electricity production in 2050.

25 Development of electricity production from offshore wind power (TWh) in the three scenarios



As of today, the necessity to base offshore wind turbines on the seafloor limits its buildout potential

FOCUS

Offshore wind

As offshore wind continues to gain prominence as a crucial catalyst for accelerating the global energy transition, numerous regions are preparing for a robust growth in this technology. This growth will be driven by the development of larger and more efficient wind turbines, which will further contribute to continuous cost reductions in the industry.

HARNESSING THE WINDS OF CHANGE

The global landscape for offshore wind development is undergoing a dynamic transformation driven by various factors. Ambitious national targets, geopolitical events, and shifting policies are propelling an increasing number of projects across the globe, leading to a surge in capacity additions. Besides that, offshore wind offers a more stable production profile compared to onshore, as farms benefit from higher and more consistent wind speeds, resulting in a more reliable and predictable power generation. Furthermore, since these wind farms are not situated on land, concerns about noise and visual impact are mitigated, enhancing their acceptability among local communities.

In Europe, the ongoing Russia-Ukraine conflict has heightened the focus on offshore wind energy as countries seek energy sustainability and aim to reduce dependence on Russian fossil fuel imports. Consequently, a remarkable increase in capacity additions is anticipated as nations raise their offshore wind targets, and numerous projects are making progress in their respective development schedules. With an installed capacity of nearly 30 GW and defined national targets totaling over 350 GW to be met by 2050, Europe is set to achieve significant growth in offshore wind.[66]

The United States is experiencing a boost in the renewable energy industry, spurred by the Inflation Reduction Act (IRA). The Biden administration has set a target of installing 30 GW of offshore wind by 2030, marking the country's first national offshore wind energy goal.[67]

In Asia, South Korea and Japan are emerging as key players in floating offshore wind. Both countries are witnessing the development of larger projects in their early planning stages, demonstrating a growing interest in this sector. Vietnam, with abundant wind resources, is targeting 6 GW of offshore wind by 2030, while China set a record by constructing approximately 17 GW of offshore wind in 2021 alone, signaling its commitment to a cleaner power market. Taiwan has also implemented significant offshore wind goals, aiming for 13 GW of capacity by 2030.[68]

In Latin America, countries including Brazil, Colombia, and Uruguay are embracing new policies and regulations to foster the growth of the offshore wind industry, representing a paradigm shift in the region.[69]

Overall, these global trends highlight the increasing momentum and importance of offshore wind as a sustainable energy solution, and it is poised to play a crucial role in the global energy transition.

NAVIGATING THE TURBULENT WATERS

Supply chain

Scaling up the offshore wind industry and meeting established targets pose significant challenges despite regulatory efforts and rapid growth. Key supply chain bottlenecks and other hurdles could hinder the efficiency and the rapid expansion of offshore wind. Major bottlenecks include the limited availability of specialised vessels and equipment for installation and maintenance, lack of skilled professionals in the industry, as well as long lead times and complex logistics for manufacturing and transporting larger wind turbine components.

The recent global supply chain challenges have had a significant impact on this sector, manifesting in project delays and increased costs. It has highlighted the vulnerability of the offshore wind industry to global disruptions, underscoring the importance of diversifying supply chain sources, reducing dependence on single regions or countries, and implementing robust risk management strategies. Various analyses indicate that the wind industry could be heading for a supply chain shortage in the upcoming years, which reinforces the importance of addressing these bottlenecks.[70]

Costs

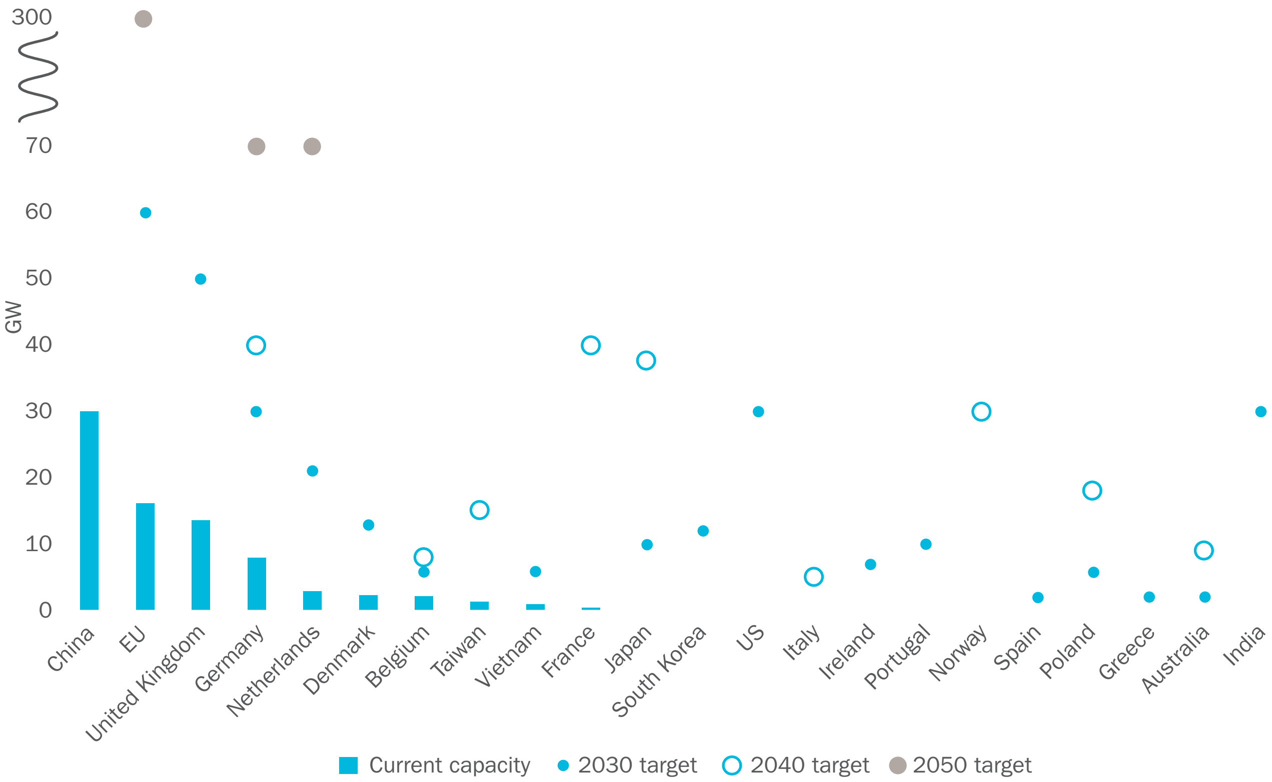
Broadly speaking, offshore wind remains less cost-competitive when compared to mainstream renewables, due to heavy reliance on subsidies for its development. The push for 'super-sized' wind turbines brings advantages but also drawbacks. While they offer increased power output and efficiency, the higher upfront costs and requirement for constant investment to continually increase turbine size is a financial burden for manufacturers. Some argue for a pause in developing larger turbines to alleviate financial pressure and allow for specialisation and optimisation of existing models.[71]

For many areas of the world, the best wind resources are in parts of the world where the sea-depth requires floating offshore installations. Floating offshore wind is a less mature technology and is characterised by higher costs compared to bottom-fixed offshore wind, due to complex design, specialised engineering, and installation requirements. Factors such as deeper water depths and limited market maturity further contribute to the increased costs, which results in the need for increased subsidisation to develop this option today. However, floating wind offers benefits such as access to stronger winds and less visual impact. Ongoing advancements are expected to reduce costs and enhance the economic viability of floating offshore wind so that, in some cases, it can become cheaper than bottom fixed offshore wind.

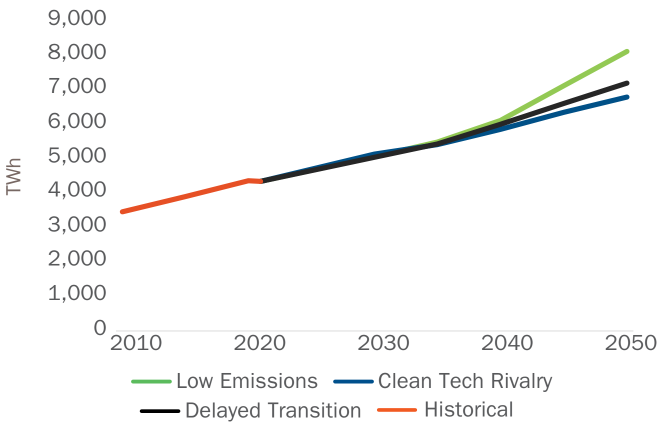
UNLEASHING THE POTENTIAL

The offshore wind industry is on the cusp of significant growth, thanks to big investments, larger and more efficient wind turbines, and a strong focus on reducing costs. However, to make the most of this opportunity, we need to address the above mentioned challenges. Suppliers in the industry are gearing up to meet the increasing demand for offshore wind projects. They are working to create a robust supply chain that can keep up with the industry's rapid expansion. Competition among these suppliers is fierce, pushing them to constantly find ways to cut costs and improve the entire sector.

26 Offshore wind targets (GW)



27 Development of electricity production from hydropower (TWh) in the three scenarios



Hydropower provides valuable flexibility to the system

In 2021, hydropower was the world's primary renewable electricity provider, generating nearly 50 per cent more electricity than solar and wind power combined.[72] Providing flexible electricity production is a unique quality for hydropower compared to other renewable technologies, functioning as both a clean energy generator and a vital storage solution. Hydropower also aids grid stability by facilitating the integration of intermittent sources like solar and wind. But hydropower's potential is limited and does not support a manyfold capacity increase as wind and solar power do. Still, **the Low Emissions Scenario** foresees a steady growth in hydropower production, resulting in a 66 per cent production increase in 2050 compared to 2021. As flexible fossil fuel power plants are gradually phased out, hydropower becomes the dominant flexible power generation technology.

The focus on energy security in **the Clean Tech Rivalry** scenario leads hydro-rich countries to exploit their competitive advantage. Accepting the additional environmental impact from building more hydropower plants, production reaches more than 8,000 TWh annually in 2050, 13 per cent more than in the Low Emissions Scenario.

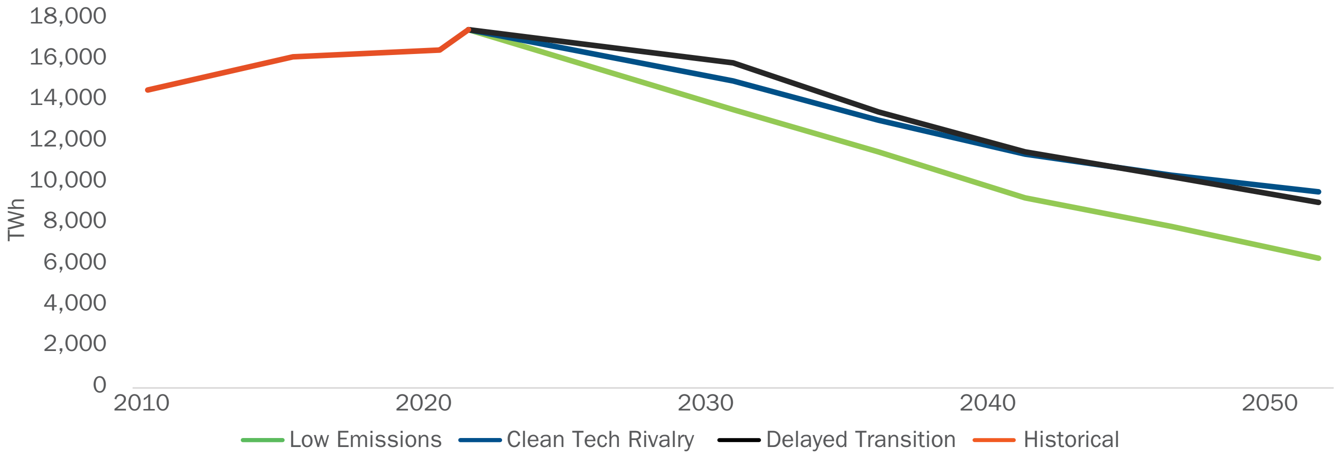
Despite less focus on the green transition, hydropower still represents a cheap source of flexible electricity generation in **the Delayed Transition** scenario, one that avoids the price swings of fossil fuels. Therefore, it still sees significant growth and provides 6,800 TWh electricity annually by 2050, only six per cent less than in the Low Emissions Scenario.

Despite less focus on the green transition, hydropower still represents a cheap source of flexible electricity generation in the Delayed Transition scenario, avoiding the price swings of fossil fuels

Location: Viddalsvatn Dam, Norway

Gas and coal generation are currently the largest sources for power generation globally, responsible for 36 and 23 per cent of the power mix

28 Development of electricity production from fossil fuels (TWh)



Fossil fuels decline in all scenarios

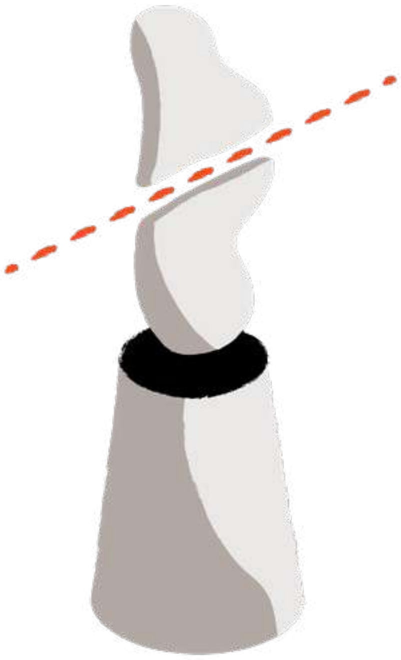
Gas and coal generation are currently the largest sources for power generation globally, responsible for 36 and 23 per cent of the power mix, respectively, and new coal and gas-fired generation is being built in several countries in Asia.

In the Low Emissions Scenario, coal power remains in a few countries in Asia towards 2050, including China, India, and Indonesia. As coal is an integral part of society in these countries, creating jobs and enhancing energy security, more government support and regulation is needed for these countries to diversify and move away from unabated coal. Carbon Capture, Utilisation and Storage (CCUS) offers a viable option to reduce emissions in large coal countries. However, CCUS is expected to have a relatively moderate role in the power sector, as costs will be high compared to other emission-free alternatives.

We therefore expect that the power mix will contain 2.6 per cent unabated coal and 5.8 per cent fossil gas in 2050. Fossil gas remains a key solution in many countries, needed to balance the increasing share of intermittent renewables towards 2050, while at the same time emitting less greenhouse gas emissions compared to other fossil fuel power generation.

In the Clean Tech Rivalry scenario, the delayed growth in renewables leads to higher fossil fuel generation across the time horizon – especially in developing countries, as fossil fuel plants with long lifetimes are built instead of renewables, locking in emissions long term. Towards 2050, more coal and gas power plants are retrofitted with CCUS to extend their lifetimes and avoid stranded assets. At the same time, this will supply the power sector with much needed flexibility, and relatively low emissions. Total generation from fossil fuels falls by almost 8,000 TWh from today to 2050.

Even **in the Delayed Transition**, fossil fuel power generation falls by almost 50 per cent. Total power demand is substantially lower, but fossil fuel power generation also struggles due to less global trade and higher fossil fuel prices, as well as difficulty competing with low-cost renewables.



Total generation from fossil fuels falls by almost 8,000 TWh from today to 2050 in the Clean Tech Rivalry

FOCUS

Nuclear power generation

In recent decades, nuclear power has struggled to advance in many developed countries. Europe and the US fight an ageing fleet, with new projects haunted by delays and rising costs. Whereas fast-growing economies in Asia, especially China and India, have more than 30 reactors under construction.

After several years in which the trend was to exit nuclear power, this energy source has recently re-entered public debate. Influenced by the increasing focus on renewable energy, many look to nuclear power as a stable, emission-free source of electricity. The Russian invasion of Ukraine sparked a major turning point for nuclear, putting energy independence as an additional argument for nuclear power. In a world beset by increasing geopolitical tension, access to nuclear power has become a strategic asset.

OPPORTUNITIES AND CHALLENGES OF NUCLEAR POWER IN LIGHT OF THE CLIMATE CRISIS

Nuclear power is perceived as a mature technology and has been an important part of the global power mix for decades, providing stable electricity production with negligible operational CO_2 emissions.

Costly and complex: As large, complex machines with a heavy body of safety regulation, nuclear power plants are inherently costly and take a long time to build. Reactor designs have constantly evolved, prohibiting significant learning effects and cost reductions (see **Fact box**). In addition, these plants are notorious for building delays and budget overruns – at least in developed countries – causing most private investors to shy away from nuclear power without governmental backing.[73]

Supply chain risk: Nuclear power might seem promising in terms of energy independence. The nuclear fuel uranium can be found in many places and is low cost, but the supply as well as its refinement industry are concentrated in just a few countries.[74] Uranium processing is also one of the best kept secrets globally, and uranium mining causes massive environmental damage.

Environmental effects: Nuclear power plants are also responsible for other significant environmental impact. Due to the large amount of concrete and steel used in the construction of the plants, the construction process causes high emissions. The local environment is affected by the plants' need for a constant stream of cooling water which typically is drawn from local rivers. The warm outlet water returned to the river can endanger aquatic wildlife. Additionally, the need for water leaves nuclear operations vulnerable to droughts and low water levels, as was the case in France in 2022. One of the most critical aspects of nuclear power from a societal perspective, however, is the radioactive waste that will be harmful for millennia to come; and the safe storage of this material remains an unsolved issue.

Safety: Nuclear power has very strict safety regulations, and nuclear catastrophes, like the ones at Chernobyl and Fukushima, are highly unlikely. The risk is there, but often exaggerated. When put into perspective, nuclear is safer than other power sources.[75]

Expertise: A long period of hibernation has drained the nuclear industry of competence and skilled workers in many countries. For a nuclear renaissance, a new generation of workers and engineers must be trained, and the manufacturing industry scaled up. A nuclear rebirth is therefore not a solution to the acute climate crisis.

A NEW DAWN

Small Modular Reactors (SMRs) are a new path for nuclear power which promises to overcome some of the hurdles of current conventional reactor designs. SMR means a small-scale reactor (≤300 MW electrical output power) with modular design. Most SMR parts can potentially be prefabricated in a manufacturing plant before being assembled on site. Uniform design and mass production of SMRs can increase learning effects and economies of scale compared to conventional reactors, which would lead to cost reductions. As of today, SMR is in the pilot stage with many players in the SMR development field distributed globally. To realise scaling effects and mass production, however, only a few can emerge successfully, and it still needs to be proven that SMR can deliver on its main promise of cost reduction. So far, these reactors struggle with the same obstacles as their conventional counterparts: delays, cost explosions, fuel sourcing, waste handling and regulation. In developed countries, we do not expect to see grid connected SMRs before 2030. And since mass deployment and scaling will take time, they will not have the potential to make a significant contribution to the power mix before the end of that decade.

FACT BOX

The cost of nuclear power

Due to learning and scaling effects, most technologies become cheaper the more they are deployed. Yet, nuclear power generation in developed countries somehow resisted this trend, with new plants getting more expensive. There are several reasons for this:

- NPPs are large, complex machines and thus inherently expensive
- Lengthy construction time causes significant additional financing costs
- Increasing safety regulation made construction more costly over time, particularly for projects already under construction
- Constant design changes prohibit learning or scaling effects
- Many manufacturers back off from the complex requirements for nuclear-grade products, compared to regular industry-grade – leading to fewer suppliers, less competition and thus higher material prices
- Long periods of little or no construction activity have drained the nuclear construction industry which painfully needs to regain that lost experience.

Asian projects (mostly Chinese, Russian and Indian) are seemingly more competitive, as they benefit from extensive state support, lower interest rates, cheaper labour, a less stringent regulatory environment and continuous building activity (trained and experienced workforce).

29 Significant events, and cost development of nuclear energy[76]

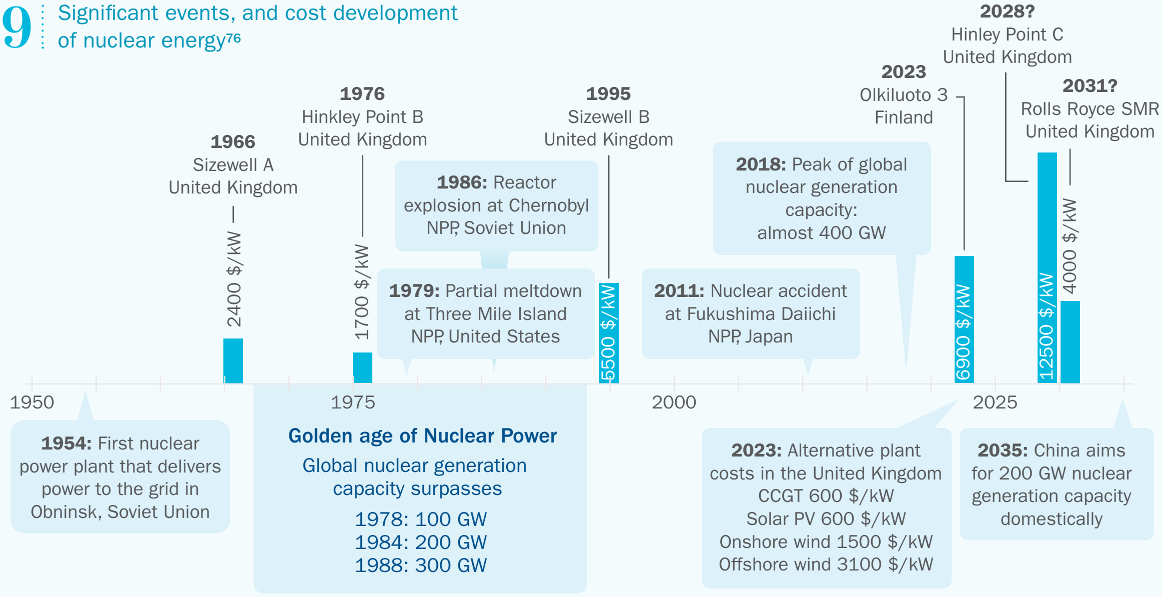
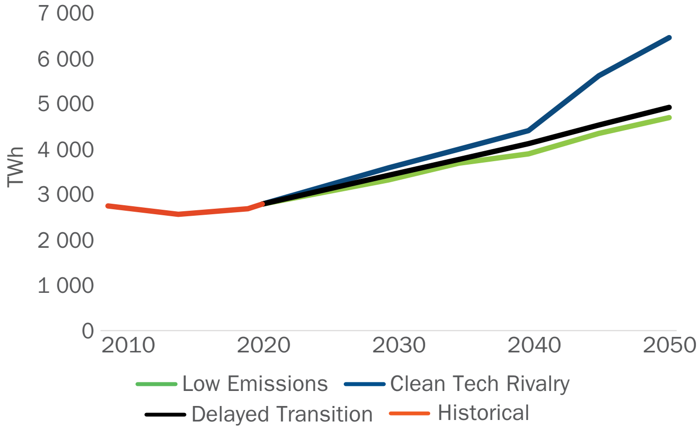


Table 1 Summary of nuclear power's opportunities and challenges in light of the climate crisis

Opportunities	Challenges
No operational greenhouse gas emissions	Capital intensive and requires governmental backing – too risky for private investors
No local air pollution	Lengthy construction time
Baseload power production	Notorious for delays and budget overruns*
Comparably small area footprint	Unsolved issue of radioactive waste
Little impact on local wildlife	Fuel sourcing environmentally damaging and dominated by few countries
In principle mature technology	Significant greenhouse gas emissions during construction
	Lack of experienced workforce*
	Risk of nuclear accidents

*in developed countries

30 Development of electricity production from nuclear (TWh) in the three scenarios



Costs and long lead times limit nuclear power's role in the Low Emissions Scenario

While public debate in developed countries focuses on the challenges of nuclear power generation (incidents, waste handling, an ageing reactor fleet, newbuilds with cost overruns and delayed start-ups), this form of power is experiencing a boom in other parts of the world. Globally, 60 reactors are under construction today, with more than half located in India and China, and many more to come.[77] As a baseload power supply with low CO_2 intensity, nuclear will play a significant part in all three scenarios.

In the **Low Emissions Scenario**, the focus on reducing CO_2 emissions causes some countries to bet on nuclear as an alternative power source. This leads to a steady growth, and electricity production from nuclear increases by around 70 per cent until 2050. Yet, the key challenges with nuclear power generation (see **Focus Nuclear Power Generation**) inhibit a massive buildout sufficient enough to be an alternative for wind and solar.

The **Delayed Transition** scenario predicts a similar trajectory, but here the driving force for a nuclear buildout is not CO_2 emission reduction but rather energy security. In a world characterised by geopolitical tensions, access to nuclear power becomes a strategic asset.

The same reason drives nuclear expansion in the **Clean Tech Rivalry** scenario. It is promoted both for providing in-demand low-carbon power for electrifying end-use sectors, as well as for its contribution to national energy independence. Large investments in research and development lead to novel reactor types that are massively deployed from 2040 onwards, pushing annual nuclear power generation to 6,500 TWh by 2050.

Globally, 60 reactors are under construction today, with more than half located in India and China and many more to come

FOCUS

Power grid

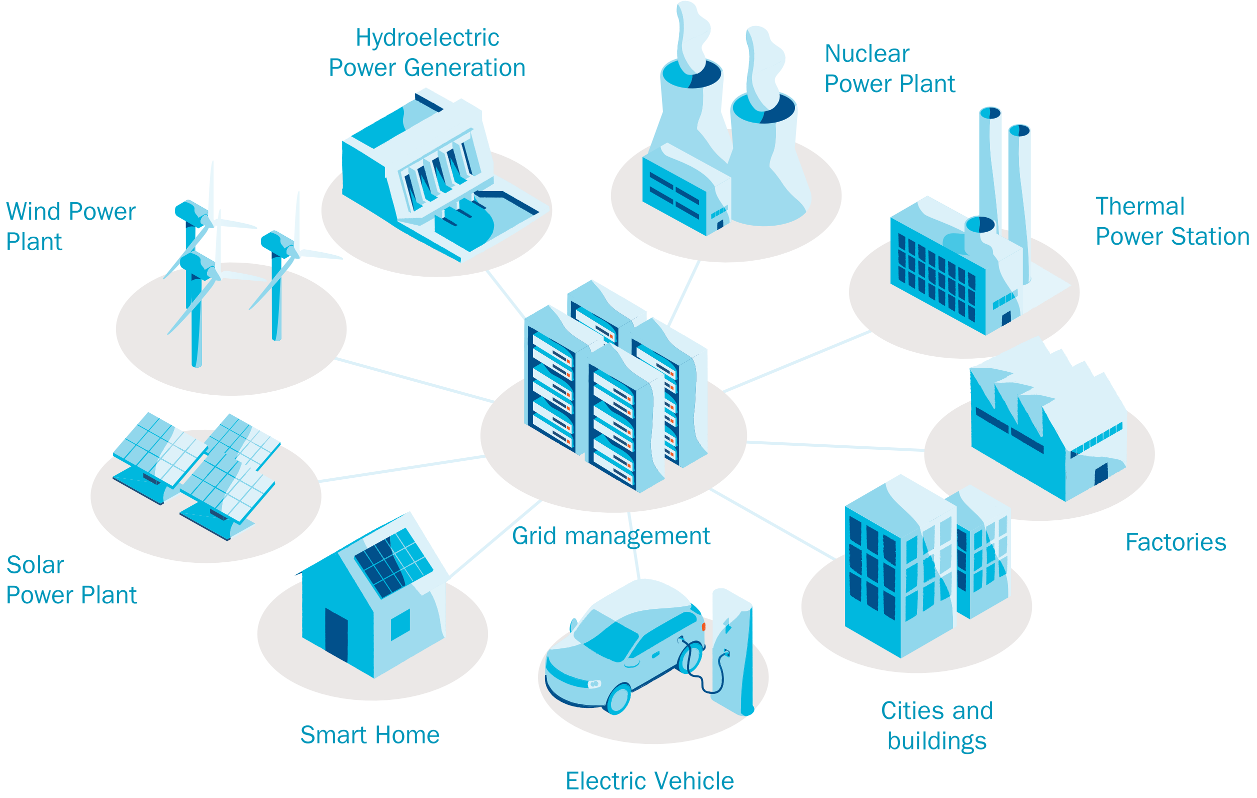
While increasing renewable power generation is key for the green energy transition, grid infrastructure is critical for ensuring efficient utilisation of the generated power. The electric grid thus assumes a pivotal role in the energy transition process. It needs to accommodate the heightened electricity demand from EVs, heating, and energy intensive industry, and ensure dependable and efficient electricity delivery amidst increasing grid intermittency due to a greater share of renewable sources.

BRIDGING THE GAP: MAKING CLEAN ENERGY AVAILABLE

To replace fossil energy with clean power, a broad upgrade of the power grid is important, to handle both the increased intermittency of power production and the increased power demand. To achieve net zero emissions by 2050, the International Energy Agency estimates that investments in transmission and distribution grids must double from around USD 340 billion (2022) to 680 billion in 2030.[78]

The intermittent nature of renewable energy sources, coupled with decentralised generation and increasing power demand, presents challenges for grid operators to maintain stability and reliability, as well as to integrate the volumes into the system. In tandem with the complexities emerging on the supply side, the demand side follows a similar trajectory, driven by the rapid electrification of the buildings, transport and industry sectors. The power grid is designed to handle current variations in demand

31 The complexities of grid management



quite effectively. However, with increased electrification, the power demand during peak hours is increasing. If everyone in a suburb charges their EVs, cooks and runs the washing machine simultaneously after work, this would cause a high risk of power outage, as the grid is not dimensioned for this heightened peak demand.

LACK OF GRID DEVELOPMENT MAY DELAY THE TRANSITION

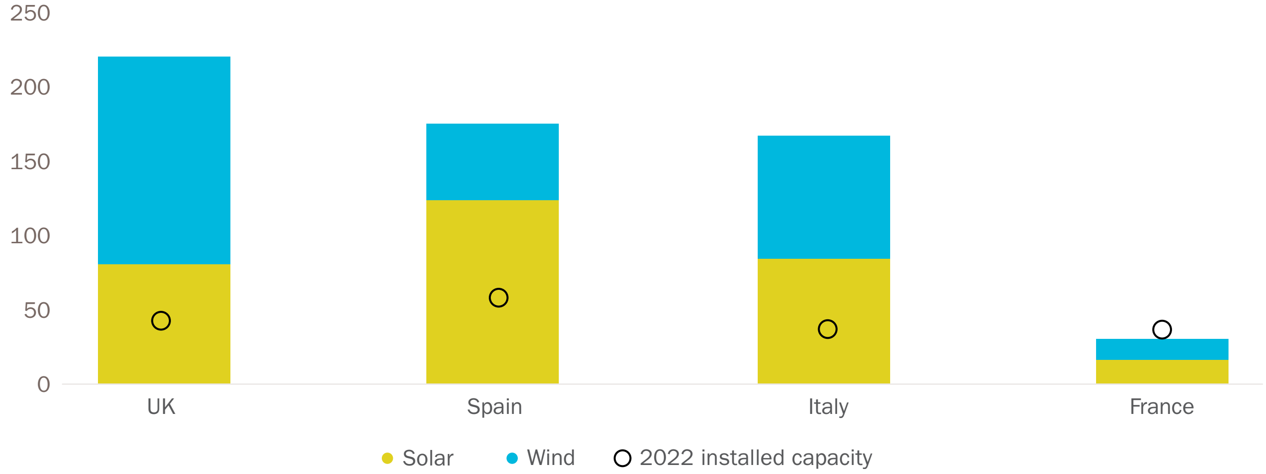
The grid could serve as a bottleneck in the green transition, as shown by the growing backlog of renewable projects awaiting grid connection permission. The interconnection queue is currently holding back nearly 1,000 gigawatts of solar projects across the US and Europe[79], which is approximately four times the global solar capacity installed in 2022. Additionally, more than 500 gigawatts of wind energy projects are awaiting grid connection, amounting to five times the wind capacity built in 2022. With many new renewable projects being commissioned, grid operators face an important task of connecting the projects to the existing grid.

The significant shift in the power mix over the coming decades requires both regulatory and structural updates to address the current market.

Solutions such as energy storage systems, demand side management, and smart grid technologies may help effectively manage the increased intermittency. Additionally, enhancing grid interconnectivity and fostering cross-border co-ordination are vital for an efficient and resilient power grid.

The average lead time for new overhead transmission lines in Europe and the US is currently around ten years, with seven years allocated for planning and permitting and three years for construction.[81] To avoid the grid becoming a severe bottleneck in energy transition, it is imperative that grid investments accelerate.

32 Wind and solar projects waiting to be connected to the grid (GW)[80]



Location: Talayuela Solar Plant, Spain

← Wind and solar power are complementary to a certain degree. There typically is little wind when the sun is shining and vice versa

Flexibility in the power system is crucial for the energy transition

Unlike other energy commodities, such as oil or gas, electricity cannot be stored in significant quantities. In a stable power grid, supply and demand must be in balance at every point in time. Logistically, this is relatively straightforward in a fossil-based power system with steady baseload supply and some flexible gas assets to balance demand variations. The output power of renewable wind- and solar-based energy sources, on the other hand, cannot be regulated up and down, but rather they depend on the weather. These sources are hence called "intermittent". Currently, these sources make up about 10 per cent of the power mix, which can be well managed by flexible fossil-based assets on the grid to balance these output swings.

The need for flexibility will grow in tandem with the increasing share of renewables. A cost-effective clean energy transition will be largely dominated by solar and wind power, considering the costs associated with flexibility provision.

In the Low Emissions Scenario, we foresee these renewable sources soaring to a substantial 67 per cent worldwide by 2050, with some regions seeing an even larger share. This is pushing the boundaries for what is possible in a power system – thus increasing the demand for flexibility. While research supports the viability of fully renewable energy systems, other clean energy alternatives could be more cost-effective if the share of wind and solar power exceeds the levels projected in the Low Emissions Scenario.

Well-connected power systems and complementary renewable technologies reduce the need for flexibility

Typically, it is cost-optimal to expand both solar and wind power in regions with a high share of variable renewable power, as wind and solar resources often complement each other. This is especially true for larger regions with good interconnections. In general, interconnected power systems reduce the need for other flexibility solutions, as the larger system benefits from the differences in each power system and increases access to flexible solutions.

This principle of power source complementation and grid connectivity does not only apply to wind and solar, but also to other renewables. Take the example of two regions: one rich with cheap but intermittent wind power and the other with an ample supply of flexible but limited hydropower. The former faces supply deficit when the wind is not blowing, the other might not have enough inflow to the reservoirs to provide power year-round. By linking these regions through interconnectors, like Norway and the United Kingdom have done, their unique strengths complement each other. When the wind is blowing, it provides enough electricity so that water in the reservoirs can be saved for periods with little wind. This collaborative setup allows the combined system to operate at its best.

FACT BOX

Flexibility - from supply meeting demand to demand meeting supply

There is no silver bullet for the provision of flexibility in renewable energy systems. Instead, the need for flexibility will likely be provided from multiple sources and solutions.

System services – providing inertia, frequency, and balancing for the grid

When supply and demand are out of balance, either more energy is drawn from the system than supplied or more energy is supplied into it than withdrawn. In both cases, the grid frequency will deviate from its design frequency (50 Hz in Europe) which can disrupt the operation of electrical devices and even lead to power outages.[82]

The grid's "first level of defence" against frequency changes is simply physical inertia. Today, most power is provided by generators (in fossil or hydro power plants) that dictate the frequency – large, heavy, fast-rotating machinery that contain large amounts of rotational energy that is immediately fed to the grid in a situation of undersupply or absorbed from the grid in a situation of oversupply. As we replace large amounts of fossil power with solar and wind, in which electricity is produced directly from sunlight and wind power the power system's stability can be challenged. Therefore, other technologies such as **dedicated synchronous generators** will be needed to provide grid stabilisation.

However, the rotational energy provided by the generators' inertia, though large, is finite. Thus, the "second line of defence" is called "fast ramping". It refers to the ability to quickly adjust the generation of electricity up or down in response to changes in demand or supply. Fast ramping power sources, like natural gas power plants, hydropower plants or certain types of energy storage systems, play a crucial role in quickly responding to these changes. In the future, **batteries** will be vital in providing fast ramping as they can react immediately to imbalances in the system with a fast frequency response.

Short-term intraday flexibility

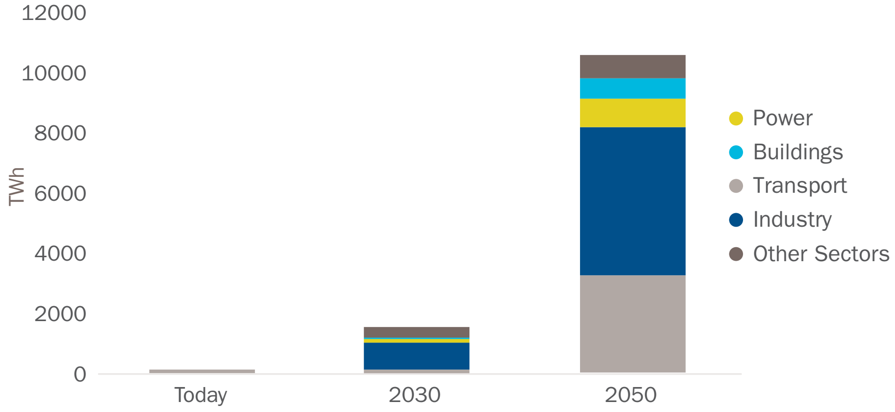
Countries and regions with a high share of solar and wind power will require solutions that move supply from high generation hours (at noon, when the sun is high) to hours where demand is higher (typically in the morning and evening), called intraday flexibility. It is likely that the need for such short-term flexibility will be met by multiple solutions. In addition to **hydropower** with or without pumping, **batteries** are regarded as a key technology to provide flexibility for shorter periods of time, such as a few hours. For batteries, costs are expected to decline in line with the steadily increasing total volume of batteries being produced. **Demand response** involves many solutions to adjust electricity consumption patterns according to variations in power supply. This will be increasingly important as supply side flexibility declines. In addition, solutions such as flexible use of electricity in heating systems and other types of sector coupling, flexible clean power production, and even currently immature storage technologies may add valuable short-term flexibility. These solutions can exploit the future price differences during the day with a higher share of solar PV in the power mix, thereby reducing the short-term price volatility.

Long-term flexibility covering weeks and months

Ensuring flexibility over longer periods spanning weeks, months, seasons, and even years helps manage situations such as extended periods of low wind, heightened energy demand during winter, or variations in energy needs between different months or years. As for short-term flexibility, meeting these long-term flexibility demands requires a combination of a wide range of solutions. For areas with access to flexible hydropower, **upgrading and expanding existing hydropower infrastructure** emerges as a cost-effective, emission-free strategy to address these extended flexibility requirements within the electricity market. Other regions might turn to **long-term hydrogen storage solutions**.

Other solutions that may contribute to long-term flexibility include interconnectors between areas with different weather patterns and power mixes, nuclear power, natural gas power with CCUS, bioenergy, and flexible heating systems that can use energy carriers other than electricity during periods of excess electricity demand.

33 Global consumption of clean hydrogen per sector in the Low Emissions Scenario (TWh)



The role of hydrogen

As climate ambitions increase, the attention is increasingly shifting towards emissions where electrification isn't a viable solution. Clean hydrogen is a key to climate change mitigation in these hard-to-abate sectors and may also become a major source of flexible power consumption. In the Low Emissions Scenario clean hydrogen plays an increasingly prominent role in the energy system.

As outlined previously in this report, hydrogen as a feedstock and as an energy carrier can be an important solution to decarbonise hard-to-abate sectors such as steel production or long-distance transport, for example. In addition, hydrogen-producing electrolysers can flexibly adjust their power consumption according to supply availability: producing in times of ample sunlight and stopping production when there is little wind, for instance.

The cost of electrolysers and the price of power will determine the price of green hydrogen, and costs are expected to decline due to greater standardisation, automation, and technology improvements. Blue hydrogen costs, on the other hand, depend largely on the cost of fossil gas and CCUS. The capital cost for blue hydrogen will be considerably higher than for grey hydrogen production without carbon capture. At the same time, operating costs will increase. In addition, the cost of transporting and storing carbon may be considerable.

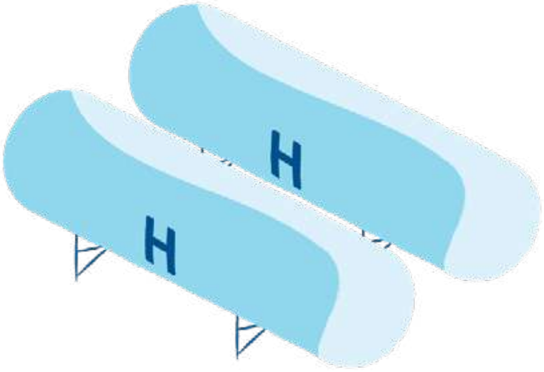
As electrolysers become more flexible, they will also be able to provide system services. Electrolysers will therefore not only provide hourly, daily, and weekly flexibility, they will also be flexible enough to stop or start production in a matter of minutes to help the power system deal with short-term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

Flexibility provision from hydrogen in the power system may be larger if hydrogen is stored. For regions with significant seasonal power price differences, like in Northwest Europe, seasonal storage can be beneficial. Storage in salt caverns is projected to be the most cost-efficient method for longer durations. Compressed tanks are preferable for short-term storage – for instance in places with high solar PV shares, like Chile, where hydrogen storage can be used to manage price differences during the day.

In the short term, hydrogen production will likely be located close to sites with high industrial or transportation demand due to limited hydrogen infrastructure. Over time, hydrogen transport infrastructure is expected to expand. Trucks, carrying compressed

← Hydrogen as a feedstock and as an energy carrier can be a solution to decarbonise hard-to-abate sectors like steel production or long-distance transport

or liquid hydrogen, are the economical choice for small volumes and short distances. Repurposed fossil gas pipelines will serve larger volumes and medium distances, and converting existing gas pipelines to hydrogen pipelines could create a connected European hydrogen market. Long-distance shipping transport may convert hydrogen to ammonia, though this incurs added costs. Substantial amounts of energy are lost when generating power from hydrogen. First, about 20 to 30 per cent of the energy is lost in the electrolyser, and thereafter another 40 per cent is lost in power generation (unless the waste heat is utilised in other sectors, such as district heating). This implies an overall energy loss of 60 to 70 per cent. However, in some situations, such as winter weeks with low renewable power production and high consumption, the lack of other alternatives may imply that hydrogen-based power generation is an attractive emission-free peak power solution. The investment cost for hydrogen turbines is relatively modest compared to alternative solutions, which is crucial for production capacity with limited running hours.



Green hydrogen's competitiveness will improve over time, influenced by power and fossil fuel prices, regulations, taxes, carbon prices, and support

- ● Renewable (or "green") hydrogen is produced from renewable power in electrolyser and is emission- free.
- ● "Blue" hydrogen is produced from fossil gas with CCS and is 90-95 per cent emission-free while "grey" hydrogen is produced from fossil gas without CCS and emits 9.9 tCO_2/tH2.
- ● "Grey" hydrogen is predominantly produced from fossil gas through steam-methane-reforming (SMR), and it is primarily used in refineries to remove sulphur from fuels and in production of ammonia today, responsible for around 2 percent of global greenhouse gas emissions.

Hydrogen demand is today split almost fifty-fifty between oil refineries and ammonia production. In Statkraft's **Low Emissions Scenario**, hydrogen consumption will increase to over three times today's consumption in 2050, and will become 100 per cent emission-free, gradually replacing all the world's existing fossil hydrogen consumption, and contributing to the decarbonisation of the hard-to-abate emissions in the industry and transport sectors (Figure 33).

The increase in total hydrogen demand towards 2050 will primarily be from new uses of hydrogen, such as in the steel industry and long-distance transport (including clean ammonia for maritime transport).

At the end of this period, we will also see some hydrogen demand in buildings and the power sector.

Clean hydrogen will cover almost 9 per cent of the global final energy demand by 2050.

In the Clean Tech Rivalry scenario, the utilisation of hydrogen encounters several challenges. The development and cost reduction of essential technologies, such as advanced electrolysers, are paramount and demand significant investment and innovative breakthroughs, which could be facilitated through timely subsidies in the Clean Tech Rivalry. However, hydrogen's reliance on renewable energy sources is impeded by supply chain bottlenecks in the renewables sector, which hinder its growth potential in the near term. Additionally, the absence of a comprehensive carbon pricing mechanism diminishes the incentives for industries to transition away from less environmentally friendly grey hydrogen, potentially leading to increased hydrogen demand compared to the Low Emissions Scenario. Furthermore, the lack of international consensus on standards and research leads to the delay of the broader adoption of low emission hydrogen, as its successful implementation also hinges on establishing efficient storage and transportation systems to support its widespread use.

As the global supply chain hurdles are overcome and technology becomes more cost-efficient, the growth of hydrogen will speed up. This acceleration will start in China, the US, and Europe, with other regions following suit as the technology development and over-supply driven by subsidies spreads. In sum, the power demand growth stemming from increased hydrogen use is around 25 per cent higher in the Clean Tech Rivalry scenario than in the Low Emissions Scenario.

In the Delayed Transition scenario, we see very limited deployment of hydrogen towards 2050. A critical factor contributing to this delay is the absence of robust policy initiatives to drive the integration of hydrogen technology. The lack of a clear policy push hinders private sector investment and innovation, stalling the progress needed. Compounding the issue, the insufficient integration of renewables in the energy mix also limits the full potential of flexible hydrogen production.

Also, the storage, transportation, and distribution of hydrogen required are largely lacking. This deficiency impedes the scalability of hydrogen solutions across industries and transportation sectors. High costs associated with retrofitting existing infrastructure and scepticism about its long-term viability are obstacles to large-scale investment. In the absence of international standards and regulations, the road to hydrogen adoption becomes even rockier. The lack of harmonised guidelines increases costs, hampers collaboration, and curbs the prospects for global implementation, reducing hydrogen's progress on the international stage.

Repurposed fossil gas pipelines will serve larger volumes and medium distances, and converting existing gas pipelines to hydrogen pipelines could create a connected European hydrogen market

FACT BOX

Carbon budgets quantify how much more CO_2 the climate can tolerate

The Earth's atmosphere acts like a greenhouse. Solar radiation is absorbed by the Earth's surface and re-emitted as thermal radiation. Part of it escapes into space while some is reflected back to Earth through molecules in the air – so-called greenhouse gases – which trap heat on the planet. The fine balance between reflected and transmitted radiation is what renders Earth a habitable planet, not too cold and not too warm, and to maintain this balance, the composition of our atmosphere is critical. For about 200 years, humans have burned fossil fuels. These fossil fuels have been extracted from below the surface, where they had been resting for millions of years, and thus when burned, emitted an immense amount of carbon dioxide (CO_2), a powerful greenhouse gas, into the atmosphere. An increasing amount of CO_2 in the atmosphere leads to a stronger greenhouse effect, causing the temperature on Earth to rise.

As of 2023, the average global temperature is about 1.1 °C higher than it was in pre-industrial times.[83] Even seemingly small increases like this have a tremendous impact on our climate. In comparison, during the last ice age, when half of Europe was covered by a kilometer-thick ice shield, the average global temperature was only 6°C lower than during the 20th century.[84] To limit climate change and mitigate the ensuing climate crisis, the milestone Paris Agreement was signed in 2015 by nearly all nations on Earth. Its goal is to limit global warming below 2°C, preferably below 1.5°C, to maintain a habitable climate as we know it.[85]

After CO_2 is emitted into the atmosphere, it remains there for hundreds of years, and global warming is therefore a result of the cumulative emissions over the last centuries. So long as we emit more CO_2 than we take up, the temperature will rise. A carbon budget quantifies the total amount of CO_2 emissions that can be released into the atmosphere while staying within a certain temperature limit with a certain probability. It considers emissions from various sources, not only the emissions from using fossil fuels in energy production, transportation, buildings, and industry, but also from deforestation, waste-management, land-use change and agriculture.

In 2023, the Intergovernmental Panel on Climate Change (IPCC), a consortium of climate scientists, calculated that from 2020 we can emit no more than 500 Gt CO_2 to keep global warming below 1.5°C with a 50 per cent chance of success. To stay below 2°C with a chance of 67 per cent, 1150 Gt CO_2 remain.[86] Global CO_2 emissions amounted to roughly 40 Gt in 2022, which means that if we continue at this rate, the 1.5°C budget will be depleted around 2030.

However, much has changed since the Paris Agreement was signed. Currently, more than 80 per cent of global emissions are covered by net-zero announcements or pledges.[87] If fully implemented, global warming could be limited to 1.8-1.9 °C. The fact that countries are willing to commit to this level of ambition is reason for hope.

Emissions: Avoiding fossil emissions is the only viable way to limit global warming

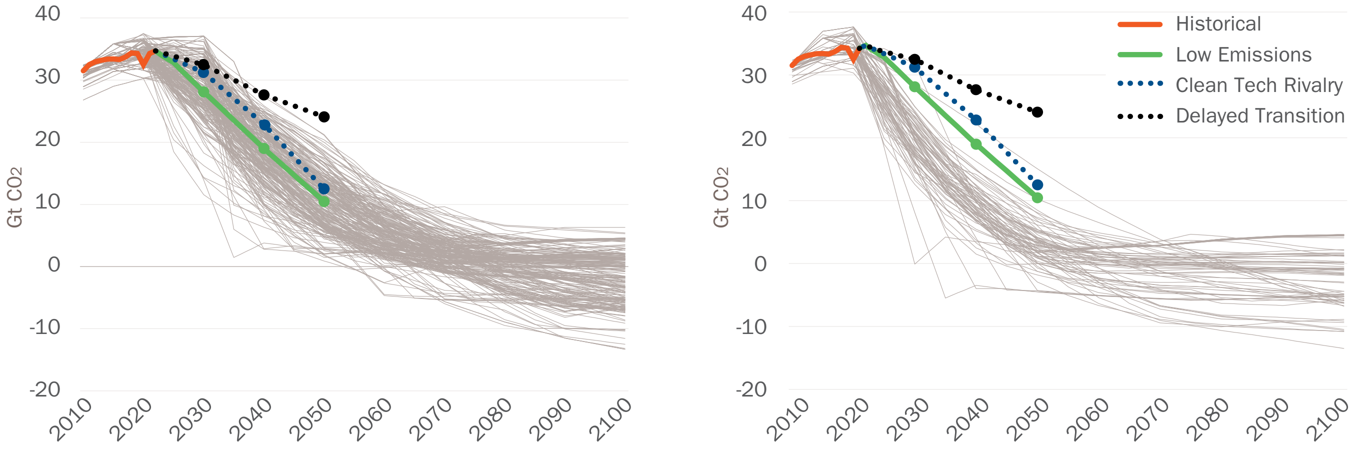
In this comparison, we look at the Low Emissions Scenario alongside the IEA's Net Zero climate scenario from the World Energy Outlook 2023, as well as the latest IPCC scenarios consistent with 1.5 and 2 °C global warming. In the Low Emissions Scenario, energy-related CO_2 emissions are projected to decrease by almost 70 per cent from current levels by 2050. While this is a significant reduction, it falls short of what is needed for a 1.5°C pathway. To align with the 1.5°C scenarios, we need to ramp up renewable energy and power generation. Additionally, a substantial increase in hydrogen and Carbon Capture, Utilisation, and Storage (CCUS) is necessary to eliminate the last and most costly CO_2 molecules.

In the Low Emissions Scenario, we consider energy-related CO_2 emissions towards 2050, which account for the majority of all CO_2 emissions. These emissions primarily result from the combustion of fossil fuels such as coal, oil, and natural gas for electricity and other useful energy.

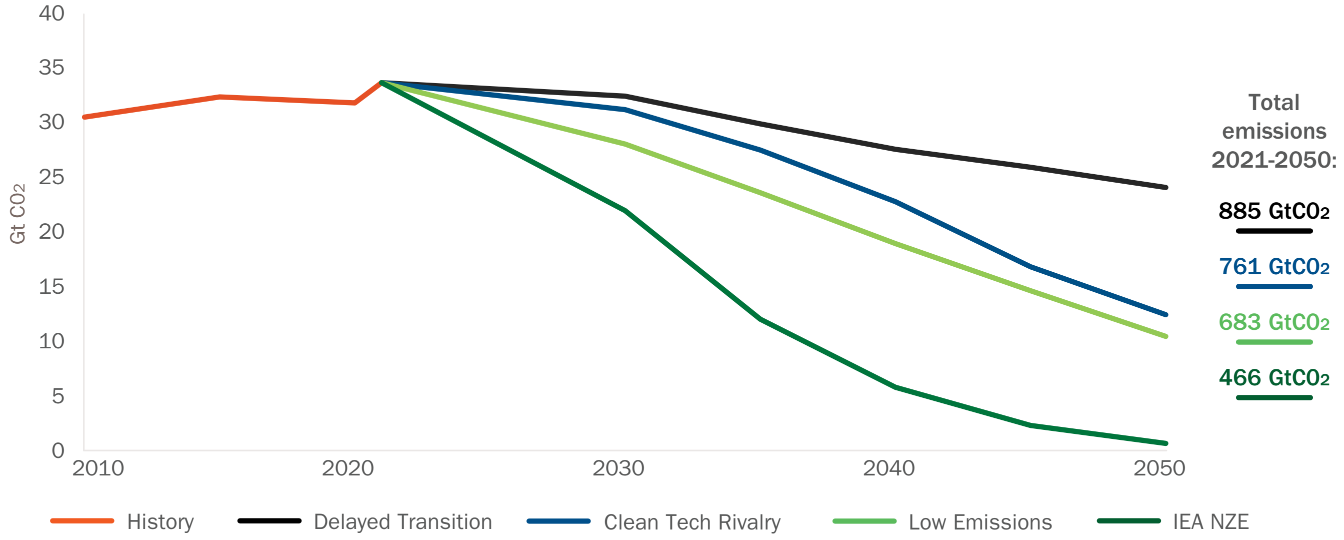
In the **Low Emissions Scenario**, global energy-related CO_2 emissions will fall by almost 70 per cent between 2023 and 2050, and we will end up with an annual emission of around 10.5 Gt CO_2 in 2050. This means that the energy-related CO_2 emissions in the Low Emissions Scenario can be in line with the IPCC's 2°C pathway if emissions are quickly reduced to zero after 2050 (Figure 34). Even so, the reduction in emissions will still not be fast enough to achieve a 1.5°C pathway.

Although the emission reduction in the **Clean Tech Rivalry** scenario almost catches up with the Low Emissions Scenario in 2050, the cumulative emissions are about 80 Gt more, leading to more global warming. This would require more net-negative emissions post-2050 to reach the same level of global warming.
The emissions pathway in the **Delayed Transition** scenario corresponds to a global warming around 2.4 °C in 2100 compared to pre-industrial times.

34 Emissions in the Scenarios vs IPCC 2°C (left) and IPCC 1.5°C (right)[88]



35 Annual Global Energy-Related CO_2 Emissions ($GtCO_2$)



The last mile to net zero

According to IPCC, global CO_2 emissions should be reduced to net zero by 2050 to limit global warming to 2°C or even 1.5°C. To reach net zero, remaining emissions must be offset by negative emissions, i.e., carbon removal. In this context, it is prudent to compare the Low Emissions Scenario with a "net zero by 2050" scenario. The Low Emissions Scenario assumes that policies, technologies, and markets mutually reinforce each other towards 2050, to gain strong energy transition momentum. Net zero scenarios, on the other hand, are often "what-does-it-take?" scenarios. A net zero scenario typically takes a back-casting perspective and establishes a pathway for reaching a net zero emission target in a certain year. In the following chapter, we compare the Low Emissions Scenario to the "Net Zero Emissions by 2050" (NZE) scenario published by the International Energy Agency (IEA) in their World Energy Outlook 2023.[89]

WE NEED MORE OF EVERYTHING, AND FASTER

In the Low Emissions Scenario, global CO_2 emissions decrease steadily, with residual 10.5 Gt CO_2 of annual emissions in 2050, yielding cumulative energy-related emissions of 683 Gt CO_2 in the period 2021-2050. At this pace, net zero is only reached after 2060, with cumulative emissions of about 750 Gt CO_2. Although carbon budget estimates are uncertain, the cumulative emissions levels likely imply a global warming higher than 1.5°C, but likely around or lower than 2°C. For the Low Emissions Scenario to be compatible with a 1.5°C pathway like the IEA's Net Zero Emissions by 2050 scenario, energy related emissions need to be reduced by almost two thirds by 2035, and accumulate to less than 500 Gt CO_2 in the period 2020-2050.

As the IEA points out in their scenario, the tools for a net-zero world by 2050 are all available, but they need to be employed at an unprecedented pace and scale. Fossil-friendly subsidies need to be removed, more wind and solar power built out faster, the electrical grid strengthened, hydrogen production scaled up, and there are also technologies that are currently in the demonstration phase that must be deployed at scale before 2050. We also need to use energy more efficiently.

Furthermore, since some emissions are very costly to abate, virtually all 1.5°C scenarios include net negative CO_2 emissions towards 2050 and beyond, such as from afforestation, bioenergy with CCUS, and carbon dioxide removal technologies.

Compared to the Low Emissions Scenario, emission reductions lag in the Clean Tech Rivalry scenario, resulting in almost 80 Gt CO_2 higher emissions in the period 2021-2050, and ending on 2 Gt higher CO_2 emissions in 2050. In this scenario, the regionalisation of supply chains delays the large-scale deployment of critical technologies and hence the reduction of CO_2 is delayed as well. This lag leads to higher cumulative emissions but could still prove sufficient to limit global warming to below 2°C.

In the Delayed Transition scenario, however, global CO_2 emissions are not even halved by 2050 and the threshold of 2°C by 2100 will inevitably be breached in this scenario.

MORE RENEWABLE POWER IS NEEDED FOR NET ZERO

Electrification is key to displacing the current use of fossil fuels, leading to a surge in electrical power generation. Both the Low Emissions Scenario and the Clean Tech Rivalry scenario follow closely behind the IEA Net Zero Scenario in terms of power generation, but neither the speed towards 2030 nor the level in 2050 is high enough to be compliant with IEA NZE in either scenario. In the **Low Emissions Scenario**, electrical energy generated

FACT BOX

Carbon removal

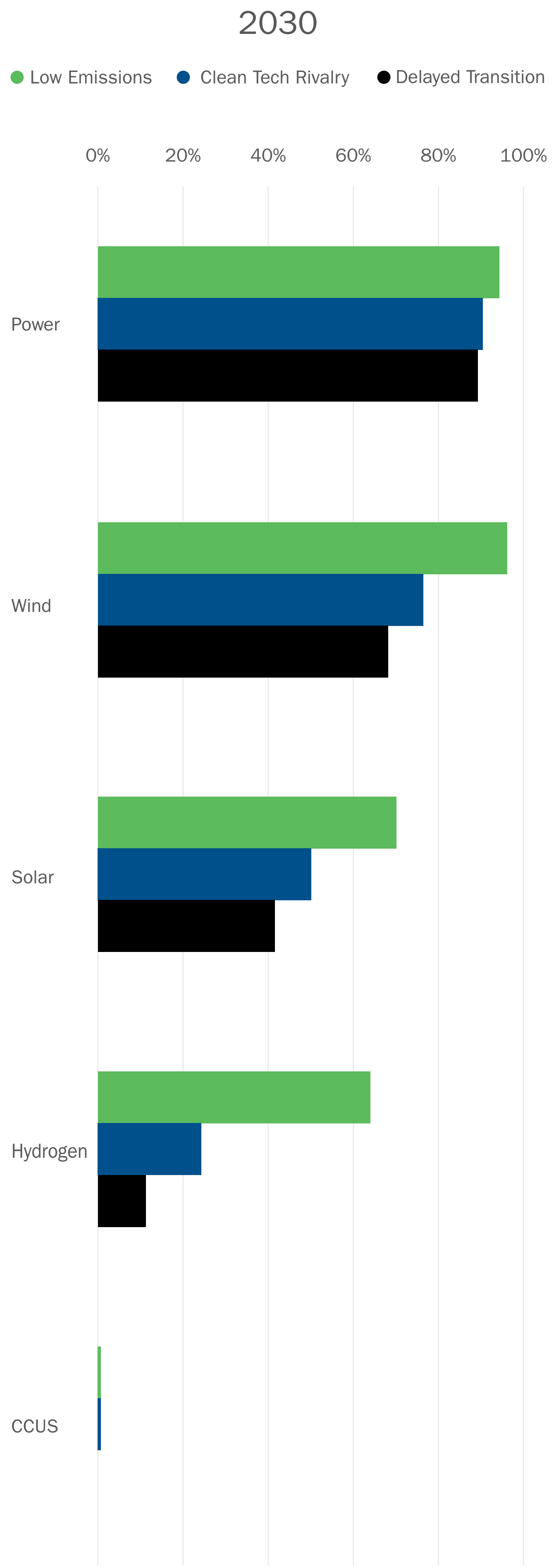
Carbon removal technologies aim at removing carbon dioxide (CO_2) from the atmosphere to help mitigate climate change. As the world faces the challenge of reducing greenhouse gas emissions to limit global warming, these technologies offer potential solutions to offset existing emissions and achieve the goal of reaching net zero or even negative emissions. There are three main types of carbon removal technologies:

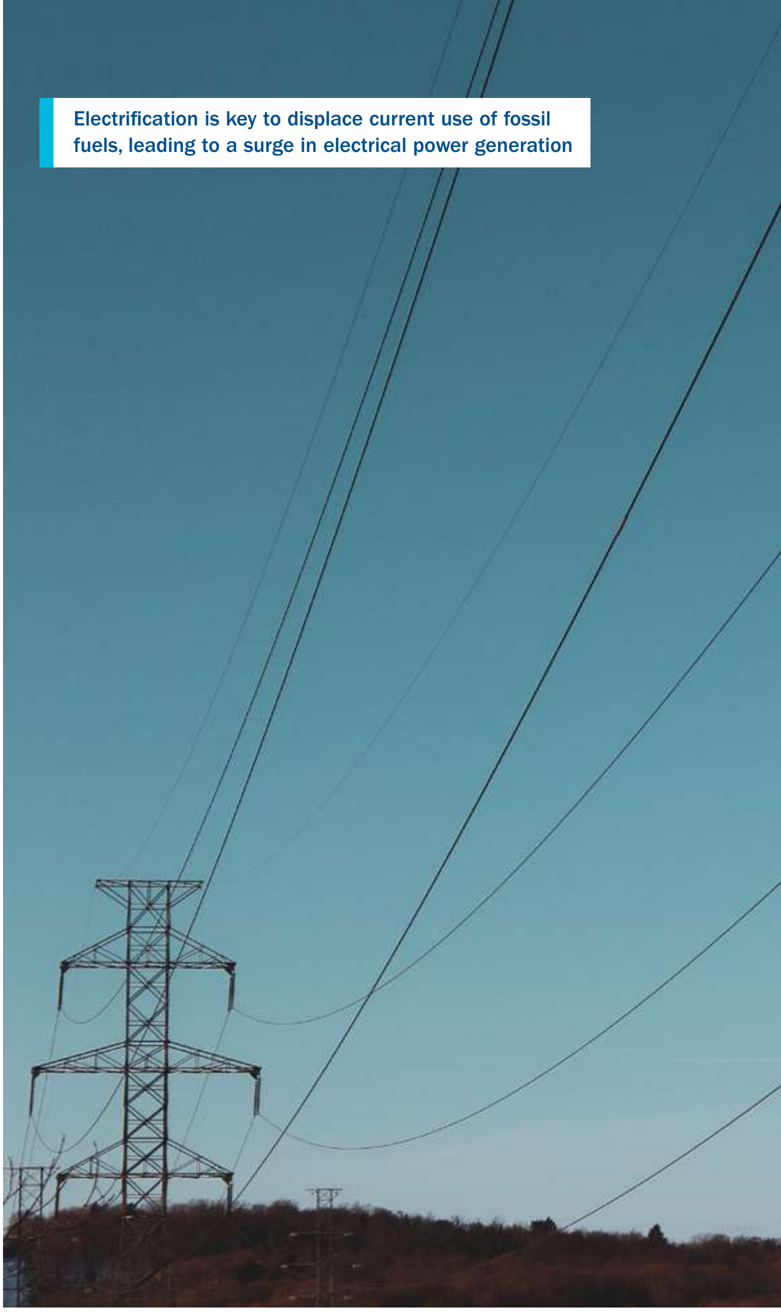
1. **Afforestation and Reforestation:** Planting trees (afforestation) or restoring degraded forests (reforestation) can capture and store significant amounts of CO_2.
2. **Direct Air Capture (DAC)**: DAC involves using specialised equipment or chemicals to directly capture CO_2 from ambient air. The captured CO_2 can then be stored underground or used in various applications, such as enhanced oil recovery or producing synthetic fuels.
3. **Bioenergy with Carbon Capture and Storage (BECCS)**: BECCS combines bioenergy production, such as burning biomass for electricity, with carbon capture and storage. CO_2 emitted during bioenergy production is captured and stored underground, effectively removing CO_2 from the atmosphere.

While carbon removal technologies hold promise, there are challenges to consider. These include the need for large-scale deployment, technical feasibility, cost-effectiveness, environmental and ethical concerns, and potential trade-offs related to land use for food production or biodiversity conservation.

↑ Afforestation and Reforestation: Planting trees (afforestation) or restoring degraded forests (reforestation) can capture and store significant amounts of CO_2.

36 Power production (total, wind, solar), hydrogen production and CCUS usage in the scenarios compared to IEA’s NZE scenario in percentages of NZE volumes (%) in 2030.





from solar is slightly higher than wind power in 2050, with 22,000 TWh and 20,600 TWh, respectively. The IEA’s Net Zero Scenario, on the other hand, has a substantially higher weight of solar power production (31,200 TWh) compared to wind (23,400 TWh).

Either way, the **Low Emissions Scenario** sees a slower build-out of renewable energy compared to IEA's Net Zero Scenario, especially with regards to solar power. Coming short of tripling the global renewable capacity by 2030. **The Clean Tech Rivalry** sees a substantially slower roll-out for wind and solar towards 2030, but from 2030 to 2050, wind and solar generation grow at a similar pace as in the Low Emissions Scenario. In the **Delayed Transition** scenario, wind, and solar generation in 2050 is less than 40 per cent of the corresponding generation in IEA’s Net Zero Scenario.

HYDROGEN AND CCUS ARE NEEDED IN HARD-TO-ABATE SECTORS

It is typically the most expensive CO_2 molecule remaining in the Low Emissions Scenario. As outlined above, clean hydrogen can be key to decarbonising hard-to-abate sectors like high-heat industry or long-distance transport.

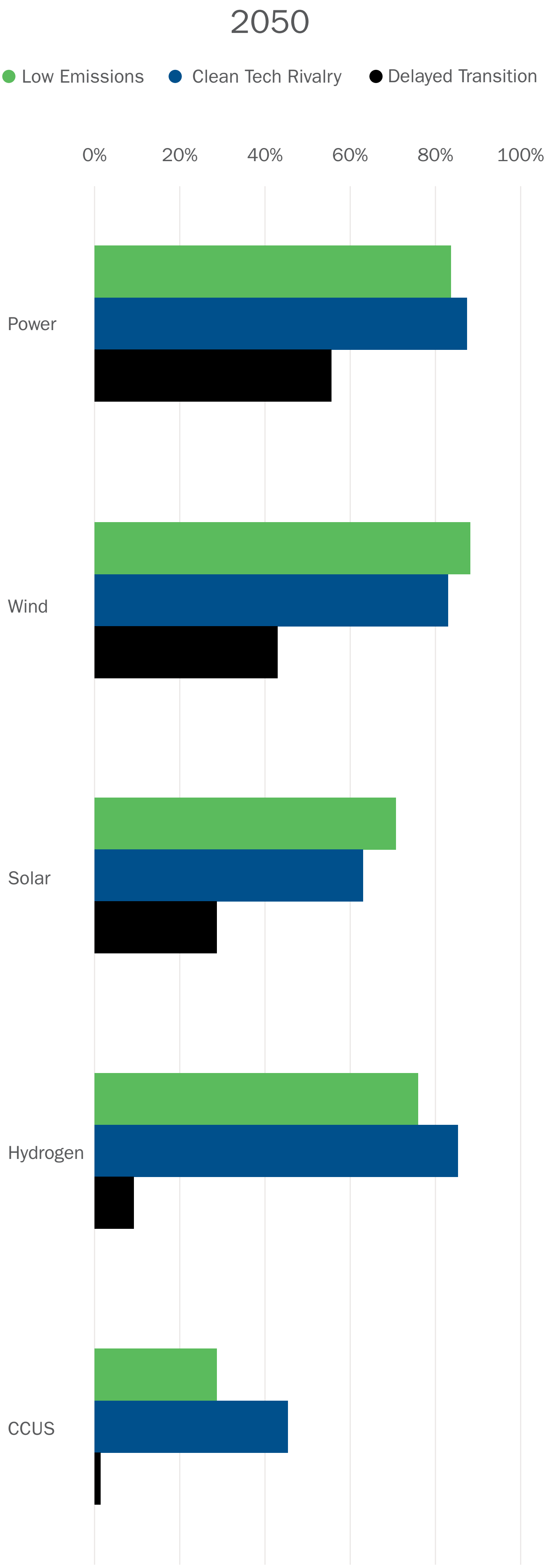
For clean hydrogen, the Low Emissions and Clean Tech Rivalry scenarios are substantially less optimistic than the IEA's NZE scenario. Hydrogen deployment towards 2030 in the Low Emissions Scenario is only just above 60 per cent of the required levels in IEA NZE, and in 2050, the **Low Emissions Scenario** anticipates about 30 per cent less clean hydrogen demand.

In the **Low Emissions Scenario**, CCUS technologies are not deployed until the 2030s, and due to high costs, it captures less than 2 Gt CO_2 annually in 2050. Less than 35 per cent of what is required in IEA NZE (Figure 37).

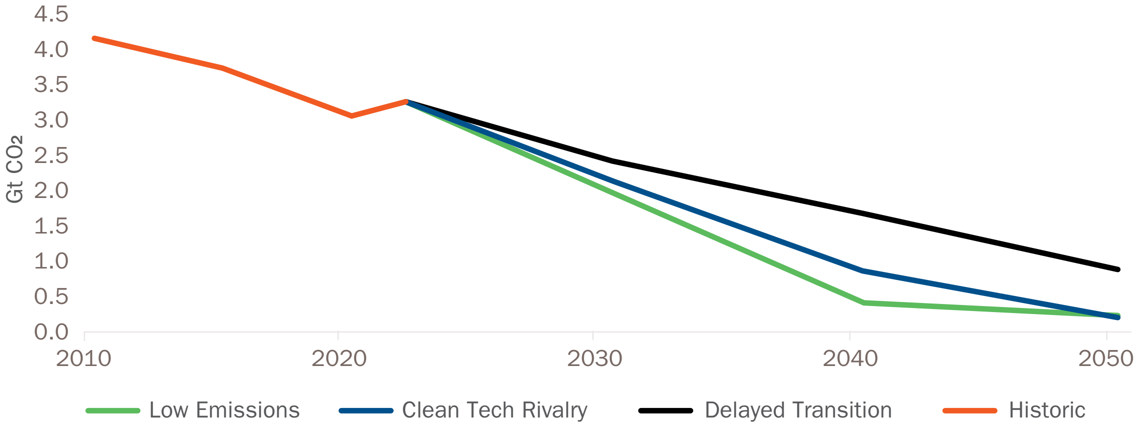
The **Clean Tech Rivalry** scenario foresees more CCUS towards 2050 than in the Low Emissions Scenario, but still far from the levels in IEA NZE. To limit global warming to 2°C by 2100, the Low Emissions, Clean Tech Rivalry and NZE scenarios rely on carbon removal technologies post-2050.

The use of hydrogen and CCUS is almost negligible in the **Delayed Transition** scenario.

37 Power production (total, wind, solar), hydrogen production and CCUS usage in the scenarios compared to IEA's NZE scenario in percentages of NZE volumes (%) in 2050.



38 Historical CO₂ emissions from combustion of fossil fuels for EU27, Norway, Switzerland, and The Balkans (2010 – 2021) and emission pathway per scenario (2021 - 2050)



A deep dive into the European energy transition

Europe has been at the forefront of efforts to mitigate climate change. In response to the recent energy crisis and soaring energy prices, the EU has set ambitious targets for the energy transition to 2030 and beyond. Similar to last year, Statkraft's Low Emissions Scenario report provides an in-depth analysis of potential scenarios for Europe's energy transition towards 2050.

Europe stands as a global frontrunner in the energy transition, having embraced ambitious emission reduction targets, combined with new regulation through the European Green Deal[i], Fit-for-55 package[ii] and REPowerEU. In addition, the EU facilitates regional co-operation and deploys a diverse range of effective and innovative policy instruments, such as carbon pricing and the Carbon Border Adjustment Mechanism (CBAM).[iii] These EU policies are aimed at accelerating the green transition and ensuring energy security, while simultaneously strengthening the EU's economic position and economic growth. So far, the energy crisis has only accelerated the energy transition in Europe.

At the same time, the war in Ukraine is testing European unity. The energy crisis and supply chain disruptions affect the region's economy due to higher energy prices and contribute to increased inflation. In this context, countries may potentially focus more on national defence, energy security and protecting national industries.

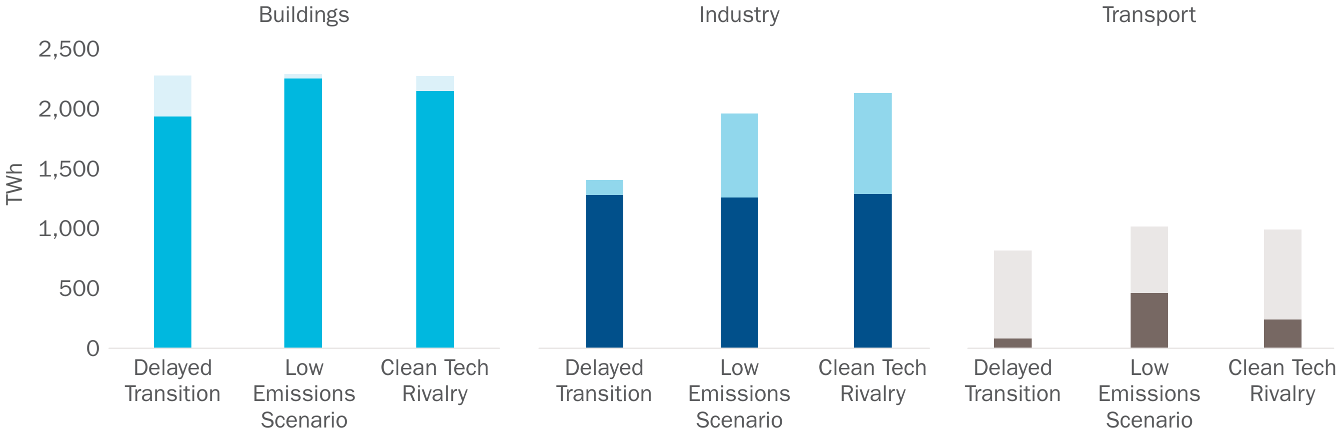
Furthermore, the European energy transition is for the time being strongly dependent on global markets, particularly for sourcing essential raw materials required for this transition. Increasing geopolitical tension might therefore affect Europe's climate ambitions at a time when access to critical raw materials is seen as a strategic asset. While the European Critical Raw Materials Act and the Net Zero Industry Act signal Europe's commitment to developing autonomous supply chains, this pursuit could inflate costs and, in the most challenging scenario, postpone the attainment of the region's ambitious transition targets.

Europe's energy transition trajectory is significantly exposed to geopolitical tension, and it varies significantly in our three scenarios:

- **In the Low Emissions Scenario**, Europe's leadership in the energy transition becomes more pronounced. The region's ambitious targets, collaborative regional efforts, innovative and diverse policy instruments such as carbon pricing, and the Carbon Border Adjustment Mechanism (CBAM), as well as well-placed subsidies, align with this pathway. The commitment to efficiency, renewables, and emission reductions hold firm, driving the transition forward. The EU reaches its goal of independence from Russian gas. However, Europe's dependency on global markets for critical raw materials remains a vulnerability, underscoring the need for resilient supply chains, as disruptions could impact the smooth progression of the transition.

- **The Clean Tech Rivalry** scenario brings both opportunities and challenges for Europe. While the region engages in a competitive race to establish clean industries and supply chains, the complex task of decarbonising existing industries while maintaining competitiveness without Russian gas emerges as a primary concern. The global subsidy race forces Europe towards a subsidy-based energy transition, with carbon price taking a back seat, leading to a less efficient and more costly transition. Limited access to critical components of the supply chains for renewable energy technologies leads to near-term emissions targets not

39 Electricity consumption from buildings, industry and transport in 2030 and 2050 (TWh) in Europe



being reached. In this scenario, some countries adopt ambitious nuclear targets to address energy security and national security concerns.

- **The Delayed Transition** scenario poses distinctive challenges for Europe. As global and regional geo-political tensions, protectionist policies, and economic concerns increase, climate mitigation is deprioritised. The political attention is instead directed towards mitigating the increased cost of living, national security and protecting essential industries, leading to delays in decarbonisation. Maintaining Europe's historical role as a climate leader faces obstacles in this scenario.

While the characteristics of each scenario present various challenges, Europe's leadership in sustainability and its ability to adapt to changing circumstances will be essential in shaping the trajectory of the energy transition within the region, as well as globally.

In our model analyses, we have run the various scenarios in our European energy system model[iv] to quantify how different emission pathways will affect the cost-optimal solution for the European transition across sectors. The analyses focus on energy-related CO_2 emissions.

- For the **Low Emissions Scenario**, we assume that EU reaches their emission targets for both 2030 and 2050, which is to reduce emissions **by 55 per cent in 2030** compared to the 1990 level, and to reach **net zero in 2050**. **For 2040**, we have adopted a more ambitious target of **90/95 per cent**, in line with "Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050".[90]

- For **the Clean Tech Rivalry** scenario, we assume that the EU does not reach its 2030 targets, as the region struggles with insufficient supply chains and trade for renewable technologies. The EU only manages to reduce emissions **by 45 per cent by 2030**, but the transition accelerates towards **2050 with the net zero target reached**.

- For **the Delayed Transition**, the emissions are only reduced **by 35 per cent by 2030**, and **80 per cent by 2050**.

Electrification in end-use sectors is key for reaching EU's climate targets

The most cost-efficient tool for reducing emissions in the end-use sectors is electrification, and mature technologies like heat pumps and EVs are key for the EU to reach its climate ambitions, especially towards 2030.

In the **Low Emissions Scenario**, technology development, markets, and policy work together, and the EU's 2030 targets are met by rolling out heat pumps as well as EVs, electrifying heating, and ensuring clean power for transport. Annual growth in heat pumps reaches well above the REPower EU targets, with 42 million new heat pumps by 2030, underlining the efficiency in cutting emissions with heat pumps (Figure 40). Electrification of industry is more gradual, as capital-intensive facilities with long lifetimes are eventually electrified. Rapid electrification takes place in parallel to the substantial growth in wind and solar power.

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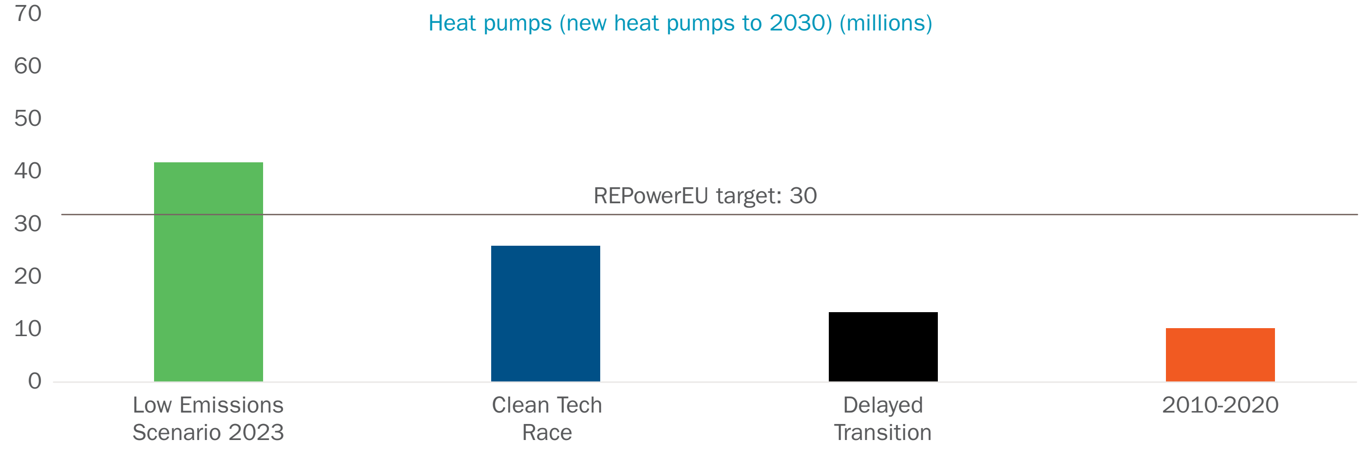
[i] The European Green Deal is the EU's plan to become climate-neutral by 2050. It covers sectors like climate, energy, transport, and more. The goal is to reduce greenhouse gas emissions by at least 55 per cent by 2030. It's also seen as a way to recover from the COVID-19 pandemic.

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

[iii] The Carbon Border Adjustment Mechanism (CBAM) is part of the EU's climate plan to prevent 'carbon leakage'. It applies a carbon price to certain goods entering the EU, encouraging cleaner global production. Importers must buy 'CBAM certificates' for their products' emissions, aligning the carbon price of imports with domestic production. The CBAM started its transitional phase on 1 October 2023.

[iv] See Annex 3 for model description

40 New heat pumps by 2030 (millions) in Europe, compared to the Low Emissions Scenario 2022 and REPower EU target



In the **Clean Tech Rivalry**, electrification slows, and the growth in EVs and heat pumps towards 2030 is 50 per cent and 40 per cent lower than in the Low Emissions Scenario, respectively. However, growth in electricity demand from transport accelerates in the 2040s to a 14 per cent annual growth, and the electrification of the buildings sector catches up with the Low Emissions Scenario in 2040. In **the Delayed Transition**, the electrification of buildings and transport is much slower, and does not catch up with the other scenarios until 2050.

Hydrogen essential in hard-to-abate sectors

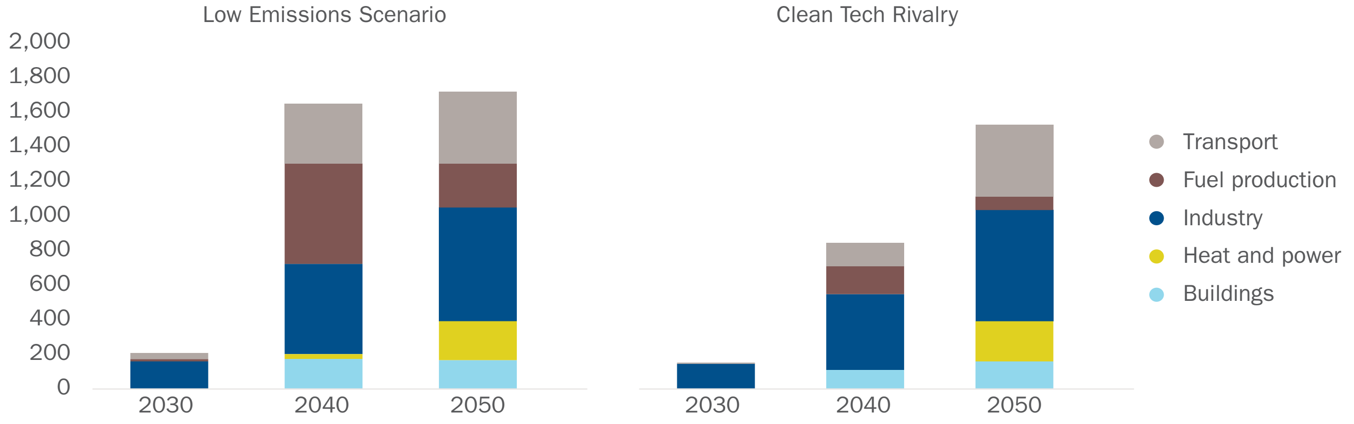
Electrolysis to produce hydrogen is not a fully mature technology. Also, demand for hydrogen requires more technology development to be available at scale. A policy push for developing the electrolyser technology and hydrogen infrastructure, along with reduced costs and access to clean power are required. These remaining challenges result in significant differences between the scenarios for the roll-out of clean hydrogen.

In the Delayed Transition scenario, power demand from hydrogen production is low, wheras hydrogen production represents a significant share of the power consumption for the **Low Emissions** and **Clean Tech Rivalry scenarios** by 2050, with 22 per cent and 19.5 per cent coming from hydrogen production, respectively (Figure 40).

In the Low Emissions Scenario, emissions are reduced by 90/95 per cent as early as 2040. This emission reduction pace requires a fast build-out of clean hydrogen, and the scenario projects an annual growth rate of 23 per cent to be attained in the 2030s. Here, green hydrogen replaces current grey hydrogen use, is used for synthetic fuel production and used directly to reduce the residual emissions in the transport and industry sectors. Hydrogen is also to some extent utilised to heat buildings and for flexibility in the power sector.

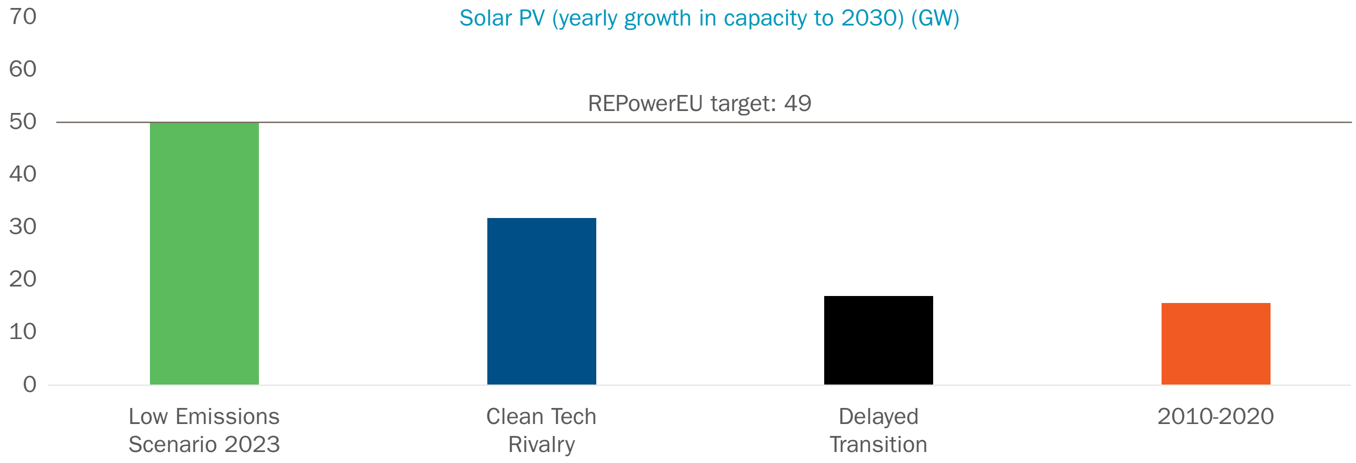
In the Clean Tech Rivalry scenario, in which the 2040 emissions target is not met, the growth in hydrogen demand is more gradual, and hydrogen is mainly used directly for heat in the industry sector or directly as a fuel in transport. This reduces emissions over time until 2050, rather than attaining the more immediate 2040 targets.

41 Hydrogen demand per sector in the Low Emissions Scenario and Clean Tech Rivalry (TWh) for Europe



Europe stands as a global frontrunner of the energy transition, having embraced ambitious emission reduction targets, and coupled it with policy through the European Green Deal, Fit-for-55 package and RePower EU

42 Yearly growth in solar power capacity 2021-2030 compared to REPower EU targets



Wind and solar may exceed 75 per cent in market share by 2050

As in the global analysis, Solar PV and wind power emerge as the winning technologies in all scenarios. Solar PV is low-cost and requires short lead times, and it is relatively flexible in terms of location. **In the Low Emissions Scenario**, solar PV deployment reaches the REPowerEU target of 49 GW per year from 2021 to 2030. Wind power reaches a growth of 26 GW per year towards 2030, short of the RePowerEU target of 32 GW per year (Figure 42).

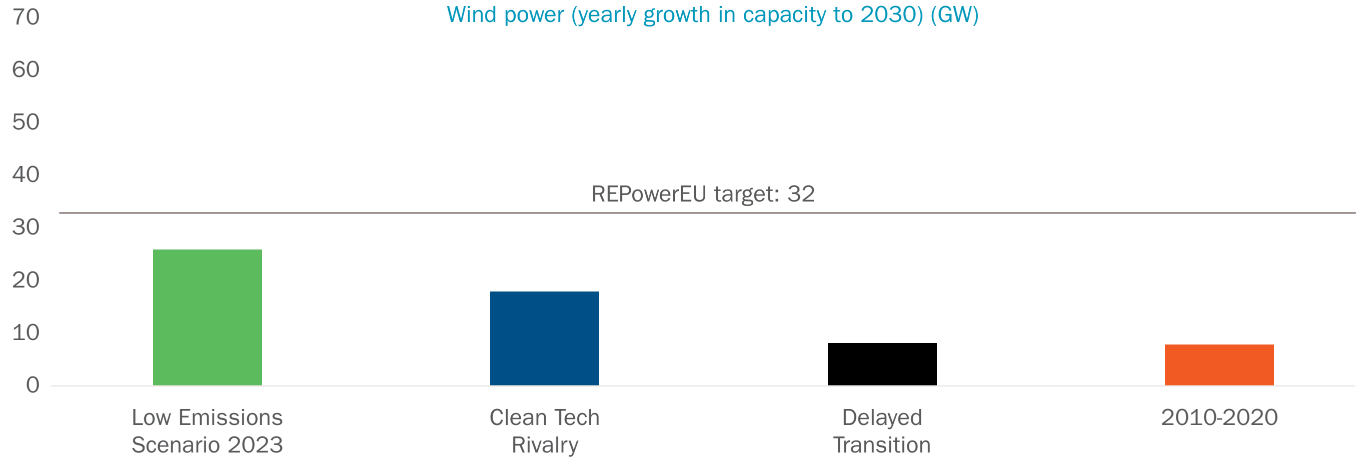
Offshore wind is currently a minor part of the European electricity mix, but the political targets for growth in this technology are massive (see **Focus Offshore Wind**). In our scenarios, growth in offshore wind capacity strongly accelerates after 2030, as result of ambitious offshore wind targets, declining costs, as well as the expanding supply chains. The relative shares of wind and solar power differ across European countries, as weather conditions, resource potential and seasonal demand profiles vary.

Renewable growth is slower in **Clean Tech Rivalry** and **Delayed Transition** (Figure 43), but even in the least optimistic scenario (Delayed Transition), solar and wind capacity grow by nearly 250 per cent from the current levels to 2050, reaching a market share of 66 per cent. In 2050, the Clean Tech Rivalry reaches comparable levels to the Low Emissions Scenario, with capacity additions accelerating to 44 GW and 36 GW per year from 2030 to 2040 for solar and wind power capacity respectively.

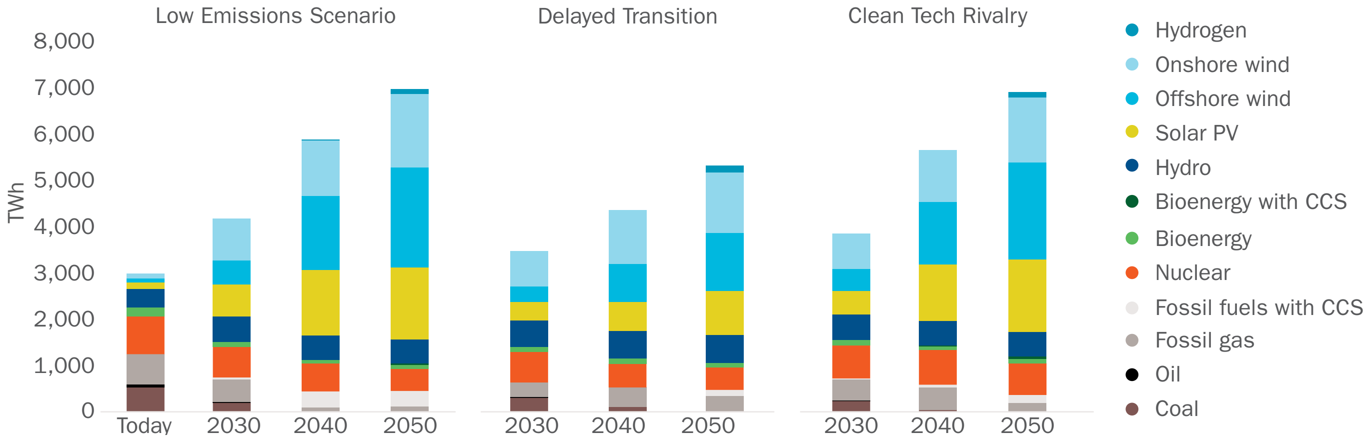
Renewable power will take on distinct roles in the deep decarbonisation of European countries towards 2050 (Figure 45). Towards 2030, the share of wind and solar increases sharply as these technologies largely replace current fossil power generation. Thereafter, wind and solar grow at an even faster pace, as renewable power also contributes to the replacement of fossil energy use in transportation, buildings and industries through direct and indirect electrification. This is the case in all scenarios to varying degrees.

← Even in the least optimistic scenario, solar and wind capacity grows by nearly 250 per cent from the current level to 2050 and reaches a market share of 66 per cent

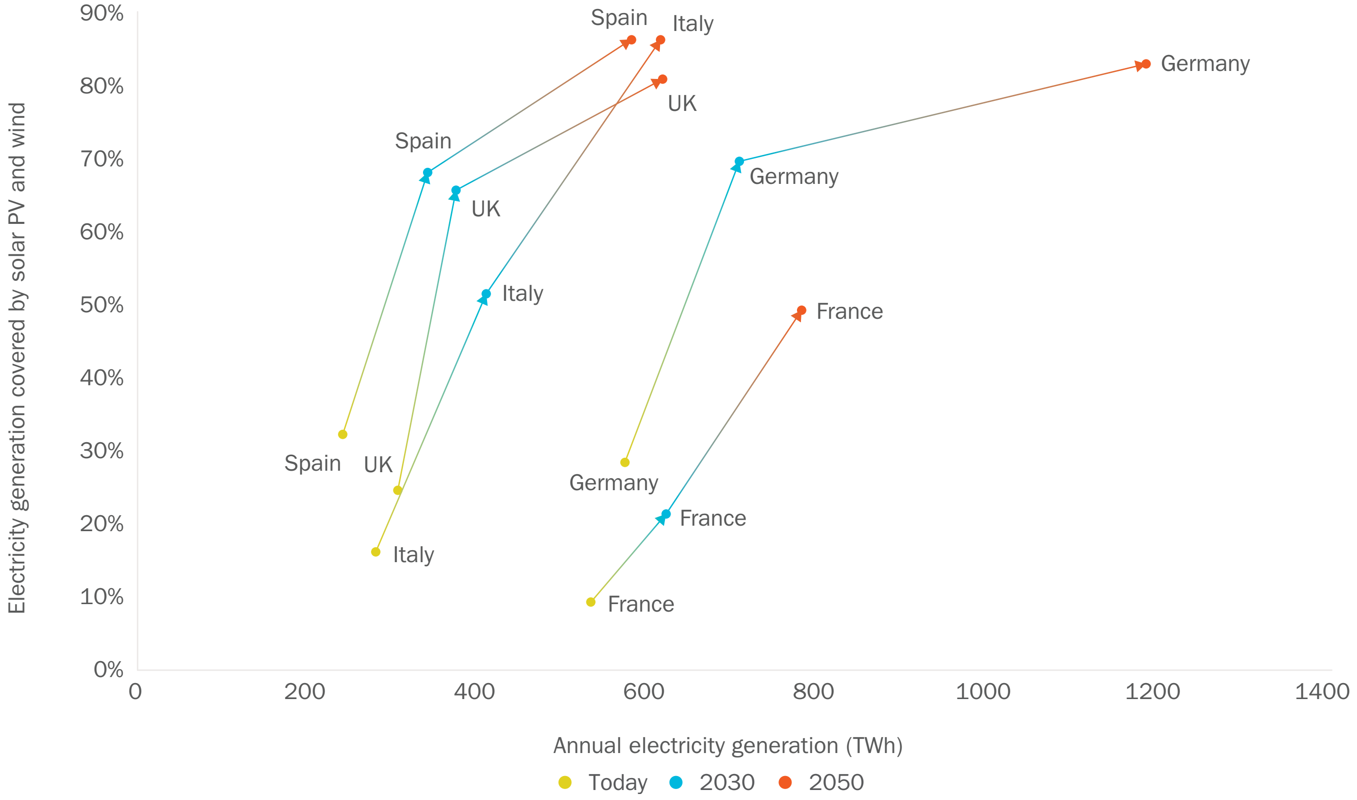
43 Yearly growth in wind power capacity 2021-2030 compared to REPower EU targets



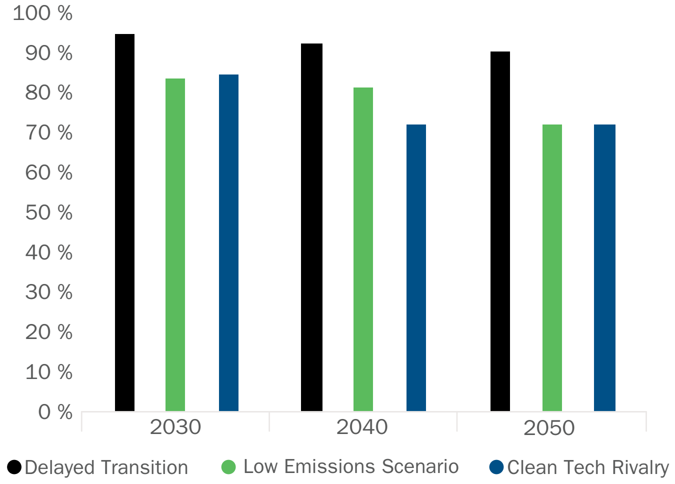
44 Power production per technology from today to 2050 (TWh)



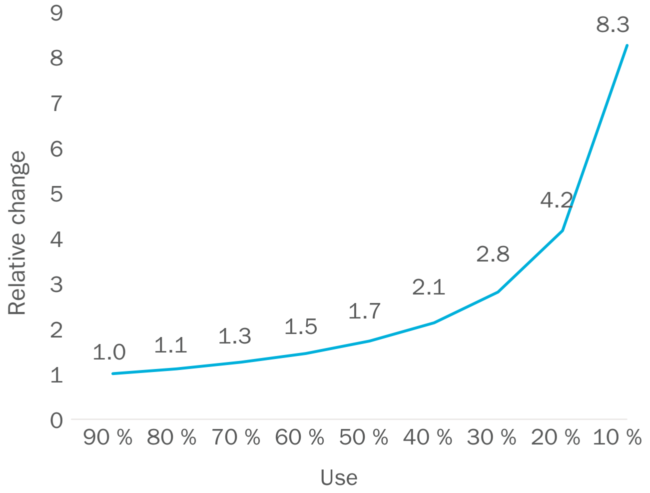
45 Regional electricity demand for major European countries covered by solar PV and wind



46 Capacity factor for nuclear power per scenario in 2030, 2040 and 2050



47 Relative change in LCOE with falling use of nuclear



The role of nuclear power is still uncertain

In the Low Emissions Scenario and the Delayed Transition, the build out of nuclear is relatively low as lead times and costs are high (see **Focus Nuclear**). However, if the European energy transition must navigate a more fragmented world, we do not rule out a more prominent role for nuclear power. **In Clean Tech Rivalry**, we assume increasing capacities in countries that currently operate nuclear plants, capitalising on their existing competence to address both national security and energy security concerns. Although more nuclear capacity is being built, compared to the other scenarios, the capacity factor is significantly lower – increasing the levelised cost of electricity (LCOE) (Figure 45 & 46). This is a consequence of low-cost intermittent renewables with zero marginal cost, outcompeting nuclear during sunny and windy hours.

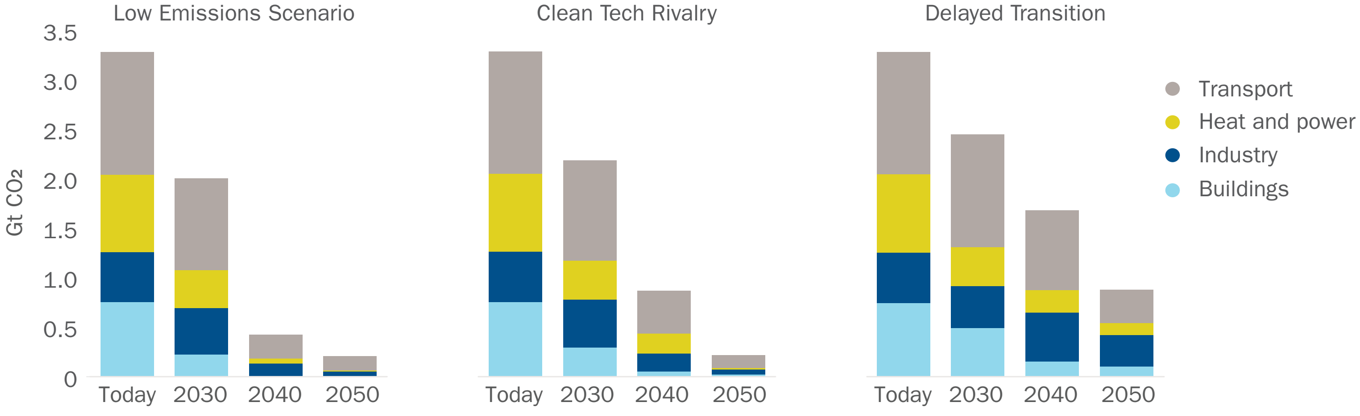
EU's climate targets are challenging, but achievable

Statkraft's Low Emissions Scenario shows how an acceleration of clean power build-out and electrification is possible and needed in the European Union to reach the ambitious emission targets for 2030, 2040 and 2050.

The energy related emission pathways from Statkraft's European system model[i] show that European emissions will continue to decline towards 2050 in all scenarios, but the speed of emission reductions will vary.

In the Low Emissions Scenario, 2030 targets of 55 per cent reductions in CO_2 emissions are met by rolling out heat pumps as well as EVs, and electrifying buildings and transport with clean power. Energy efficiency measures in buildings and industry reduce energy demand, resulting in less electricity needed to decarbonise the end-use sectors. To reach the ambitious 2040 targets,

47 European emissions by sector ($GtCO_2$) (today to 2050)



Although more nuclear capacity is being built, compared to the other scenarios, the capacity factor is significantly lower – increasing the levelised cost of electricity

considerable amounts of hydrogen are needed, especially to decarbonise hard-to-abate sectors like industry and transport. Hydrogen, along with fossil gas (with CCS) and batteries, emerge as the key technologies for flexibility in the power sector.

In **Clean Tech Rivalry**, emission targets for 2030 and 2040 are out of reach, reaching only 45 and 80 per cent reduction in 2030 and 2040, respectively. This is the case despite emission reductions accelerating towards 2040, as the clean energy value chain reaches sufficient capacity, swiftly cutting emissions from power, heating, and passenger vehicles. Towards 2050, hydrogen demand surges, primarily from industry and transport as a means to cut emissions from hard-to-abate sectors.

Emissions are significantly reduced even in the **Delayed Transition** (35 per cent and 80 per cent in 2030 and 2050, respectively). Here, the emission reductions are mostly attributed to the substitution of fossil fuels for renewables in the power sector, while electrification of end use has a slower pace and less magnitude. Protectionism and deglobalisation lead to more energy-intensive industry in Europe, and the lack of climate policy also leaves substantial amounts of emissions in the hard-to-abate sectors.

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[i] See Annex 3 for model description

Appendix

APPENDIX 1

The assumptions in the Statkraft Low Emissions scenario, compared with IEA and BNEF[91]

Sectors	Statkraft's Low Emissions Scenario 2023	IEA STEPS (2023)	IEA Net zero (2023)	BNEF NEO (2022) NZS
Annual growth in primary energy demand 2021-50	-0.43 %	0.52 %	-0.49 %	-0.20 %
Power sector				
Demand	2.88 %	2.24 %	3.50 %	3.79 %
Wind power	8.62 %	6.56 %	9.12 %	11.06 %
Solar power	11.24 %	10.2 %	12.51 %	11.34 %
Hydropower	1.76 %	1.35 %	2.26 %	0.28 %
Unabated fossil share in power sector (TWh, 2050)	8.40 %	21.06 %	0.21 %	0.14 %
Primary energy				
Oil consumption: annual growth 2021-50	-2.71 %	0.06 %	-4.96 %	-4.66 %
Gas consumption: annual growth 2021-50	-1.16 %	-0.04 %	-5.10 %	-2.61 %
Coal consumption: annual growth 2021-50	-4.87 %	-1.71 %	-8.06 %	-3.67 %
Global energy-related CO_2 emissions ($GtCO_2$) in 2050	10.5	26.78	0.66	0.08

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

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

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

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

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

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

WHICH EMISSIONS ARE COVERED IN THE LOW EMISSIONS SCENARIO?

The emissions analysed in the Low Emissions Scenario are energy-related CO_2 emissions. These are emissions from fuel combustion (excluding the incineration of non-renewable waste). Other emissions that are not included are diffuse emissions (i.e., leaks, emissions from the transport and storage of fuel, etc.) and industrial process emissions.

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

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

The emissions are broken down into the power sector, buildings sector, transport sector, industry sector 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 emissions from iron and steel production, the chemical and petrochemical industry, cement and the pulp and paper industry. Emissions from vehicles that are not used on public roads are also included.

- **Other sectors:** Emissions from non-energy use and from agriculture, in addition to emissions from the production and transformation of fuels, i.e., emissions from, for example, oil and gas production, coal mines and petroleum refineries. '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.

APPENDIX 3
ETM Model description

The Statkraft Energy Transition Model (ETM) has been used to analyse the consequences of the REPowerEU plan. ETM is a techno-economic optimisation model covering the entire energy system of 29 European countries/regions, especially suited to analyse complex interactions between supply and demand of energy. The model aims to supply energy services at minimum total cost by making equipment decisions, as well as operating, primary energy supply and energy trade decisions.

APPENDIX 4
Scenario descriptions

Table 2 Scenario description color coded by effect on energy transition
Blue: significant positive effects on the energy transition;
yellow: somewhat negative effects; red: negative effects

	Scenario		
	Low Emissions Scenario	**Clean Tech Rivalry towards Net Zero**	**Delayed Transition**
Economic growth	Global economic growth following successful actions mitigating the impact of inflation.	Less global trade and more regionalisation leads to lower economic growth. Less efficient allocation of resources.	Slow growth in most regions, inflation, high unemployment, and poverty increasing in the West.
Climate policy	Strong political support for energy transition – policies strengthening market mechanisms.	Strong political push for energy transition (subsidy-driven) as solution both for climate and security of supply – competition to dominate future tech.	Nationalisation of energy markets. More nuclear and fossil as solution to energy crisis.
Carbon price	Carbon pricing expanding globally. Higher acceptability for carbon pricing instruments. Less overlapping policy instruments. Carbon price reflecting the marginal abatement costs.	Subsidies in China and US put pressure on Europe. Other policy instruments than carbon pricing are preferred in all markets. Lower carbon prices.	Far left/right forces gain power in Europe and elsewhere. Weak climate ambitions. EU unity weak. More national policy instruments and diverging carbon pricing between countries.
Global trade	Well-functioning global markets, Regionalisation trend is reversed.	Increasing degree of regionalisation (esp. technology), but with some global trade (esp. commodities) – need time to establish new value chains.	Some global trade but decreasing due to home-sourcing and less economic growth.
Geopolitical situation	Stabilisation in geopolitical environment globally over next 1-2 years.	Two block world (“cold war”-like)– “competing” on dominating technology, ideology.	Each region focused on internal problems - nationalisation as “solution”. Limited int. cooperation on climate issue.
Internal West relations	Strong relations within EU and between US and EU. Reduced protectionism.	Ideological unity between EU and US, and shared tech development but some protectionism between the two (i.e. IRA).	Weak EU – more national and diverging solutions to energy crisis. Weak EU-US relations (more trade barriers).
China – West relations	Improved from today - China – US/EU relations built on “agreed rules” including extensive trade.	China leader of the “non-West” block. Trade that both parties benefit from, but less with sensitive goods (e.g. high tech).	Less trade, both China and West more inwards looking.
Rest of the world	Strong economy fuelled by global economic growth and cooperation.	Will seek neutrality and benefit from trade with both blocks. Slower transition first, but will later benefit from lower tech cost.	Affected by poor economic outlook. More room for opportunistic state leaders taking regional role.

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