A Low Carbon Development Scenario for Europe

The role of the North Sea in European decarbonization.

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Further contributions to this report were made by Geir Haakon Hilland and Johannes Struweg, including assisting with research, writing and revising the manuscript. The design of the report was completed by Renate Bakkeslett Hagen and Marius Istvan Harlem-Nilsen.

Contents

Executive summary

To become carbon neutral by 2050, Europe has to undergo a widespread transformation from reliance on fossil energy to using clean energy throughout the energy system, The North Sea could contribute to this transformation by providing clean energy through offshore wind and hydrogen, as well enabling large-scale carbon capture and storage. These are all key components of EU strategies for decarbonization of the energy system, which by 2030 aim to have installed 60 GW of offshore wind, 20 million tonnes of annual clean hydrogen production and 50 million tonnes of annual carbon capture and storage. The North Sea stands to benefit considerably by contributing to these goals.

Reducing emissions in the electricity sector will be central to reaching the climate goals in the EU, and the North Sea can contribute to this by installing up to 200 GW of offshore wind by 2050. Following the phase-out of Russian natural gas from the energy system, the EU decarbonization goals have become even more reliant on renewable power generation including offshore wind, in order to make up for the energy deficit. The electricity sector will also need to substitute the power stability that natural gas power plants provide using other dispatchable generators, such as nuclear or coal. In the latter case, carbon capture and storage will be necessary in order to ensure that the power generation is aligned with the climate goals.

Carbon capture and storage will be an important piece in the decarbonization puzzle, and by 2050, the North Sea may store more than 15 billion tonnes of CO_2. This CO_2 can come from many different sectors, including from power generation, iron and steel, cement and hydrogen. Some of these sectors can be decarbonized using alternative means, but for others, e.g. the cement industry, it is challenging to reduce emissions sufficiently without carbon capture and storage to align with the climate goals.

Hydrogen is regarded worldwide as a key component to decarbonize hard-to-abate sectors, such as long-distance transport, and the North Sea can be a key source of energy for hydrogen production. Using plentiful natural gas reserves, the North Sea could provide blue hydrogen – hydrogen produced through natural gas reformation combined with carbon capture and storage – thereby enabling large volumes of low-cost hydrogen. Alternatively, the North Sea region can also use offshore wind energy in electrolyzers and produce green hydrogen. Electrolyzers can use excess and cheap electricity to produce hydrogen for storage, or used in non-electrified sectors, thereby synergizing well with a renewable power system. Regardless of whether blue or green hydrogen becomes most attractive in Europe, the North Sea will be able to be a key supplier of hydrogen in the future.

Realizing the potential of the North Sea will require close international collaboration in order to produce, transport and consume energy in the most efficient ways. This necessitates significant investments into electric transmission grids in the North Sea, as well as ships and pipelines to transport CO_2 and hydrogen in Europe. Countries in Europe have started creating common ground, including shared EU strategies and infrastructure plans. These projects will need to be funded by both governments and private investors to ensure the plans are realized.

Europe aims for carbon neutrality by 2050, and the North Sea can contribute

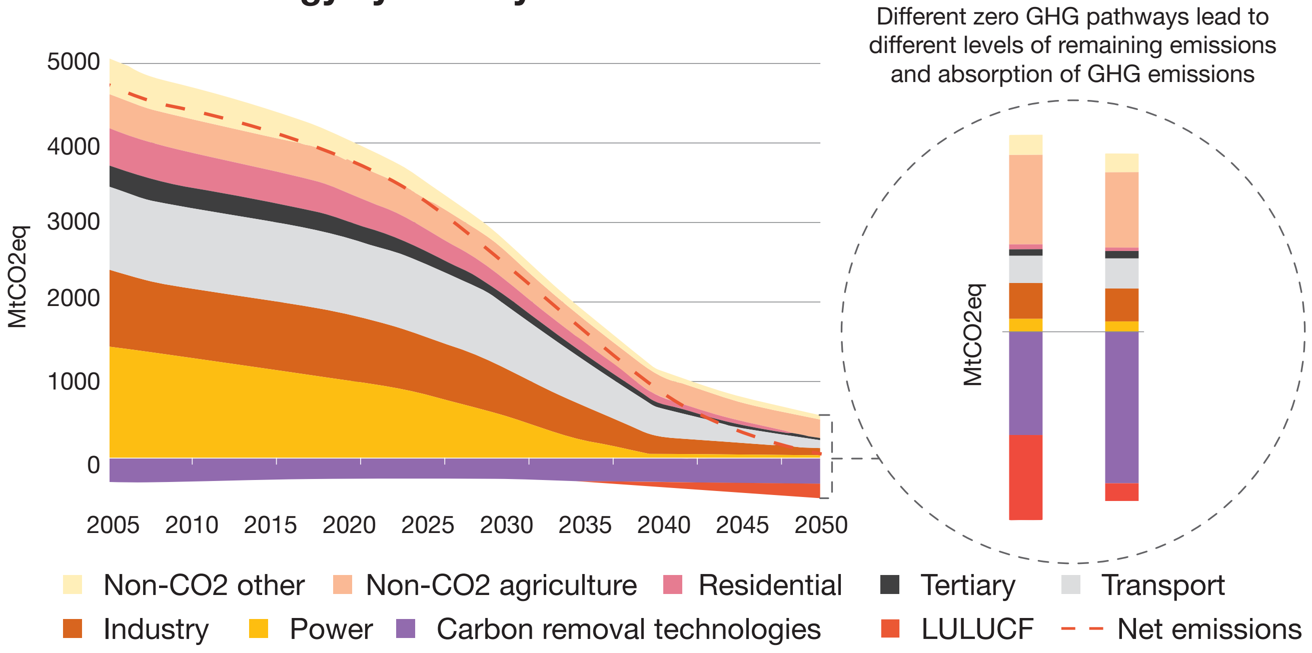
The European Commission has set a goal of significant reductions of greenhouse gas emissions. Achieving this won't be simple, and the solutions need to balance energy security, affordability and low emissions. To realize its goals, the European Union (EU) will have to use all available resources, and the North Sea can be a key asset in this pursuit. The North Sea has a high potential for offshore wind, vast capacities for permanently storing CO_2, and large quantities of natural gas that can be used to phase out coal, or produce hydrogen. This report describes a scenario for European decarbonization and demonstrates how these resources can make North Sea the focal point for a cost-effective European decarbonization.

Combating climate change has been a central issue for the EU, and was formalized in the European Green Deal[1]. Therein, the EU committed to reducing its greenhouse gas emissions with 55% by 2030 compared to 1990 levels, and reaching climate neutrality by 2050.

> *The European Green Deal is our new growth strategy – for a growth that gives back more than it takes away. It shows how to transform our way of living and working, of producing and consuming so that we live healthier and make our businesses innovative.*
> – EU president Ursula Von Der Leyen[2].

The European Commission also proposed a strategy of reaching climate neutrality by 2050, which includes large reductions of greenhouse gas emissions in all sectors of the European energy industry. This decarbonization trajectory has been the central pathway in this analysis.

EU's climate goals are to reach climate neutrality across the energy system by 2050[3]



The EU is at the forefront of climate policy, targeting self-sufficiency in energy and critical technologies

The primary tool that the EU has implemented to achieve reductions of greenhouse gas emissions is the European Emissions Trading System (ETS)[4]. This system caps the total volume of greenhouse gas emissions for the included sectors, and covered businesses can only emit greenhouse gases if they exchange a corresponding carbon certificate. These are made available at the beginning of each EU ETS phase, and may be traded freely following the initial auction. Curently, the ETS covers power and heat generation, aviation, maritime transport and industry.

The EU is also introducing ETS2, which will be a separate system for buildings, road transport and fuel suppliers[5]. This won't become fully operational until 2027, however monitoring and reporting of emissions related to the mentioned sectors will begin in 2025.

European efforts to decarbonize have intensified in the REPowerEU plan[6]. This was introduced in response to the energy crisis that emerged once Russian pipeline gas was phased out of the European energy system in 2022 following the Russian invasion of Ukraine. The plan includes increased self-sufficiency in energy through the deployment of renewable energy production to replace fossil energy use. In this way, the REPowerEU plan contributes to realizing the 55% emissions reduction by 2030 target.

The goal of self-sufficiency and decarbonization is also a central point in the Net Zero Industry Act[7]. This act aims to increase the development and production of technologies that support the energy transition, including within hydrogen production, carbon capture and storage (CCS), and renewable energy production.

Europe's energy system is still based on fossil fuels, used mainly for energy purposes

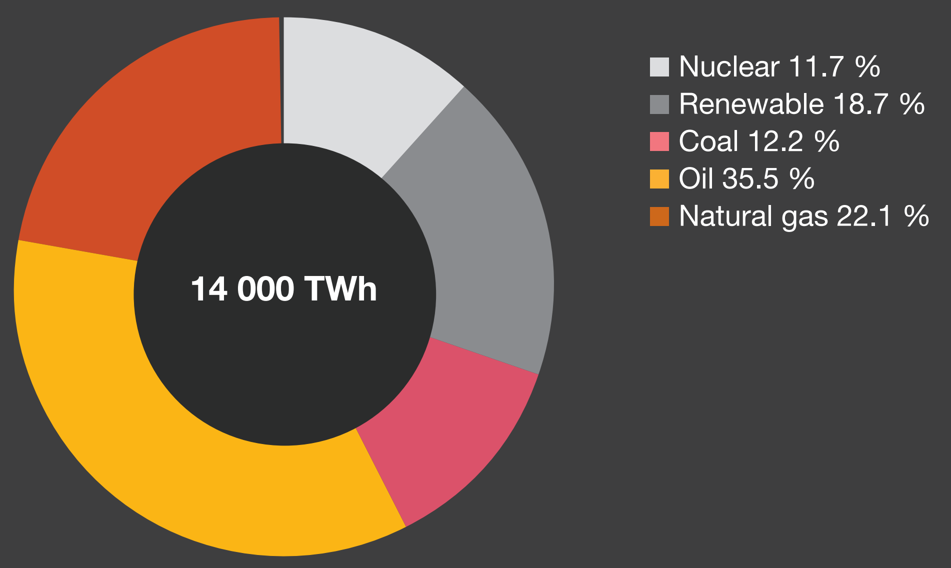
While the EU has focused on increasing the deployment of renewable energy production, the share of fossil fuels in the European energy system account for roughly two thirds of total primary energy supply today. Consequently, most of the greenhouse gas emissions in the EU originate from the energy industry.

The European energy system is large and complex, and coal, oil and gas fulfill very different needs. However, the solutions are not necessarily as complicated. One of the primary ways of reducing emissions is through electrification of transport and industry[10], while the emissions associated with electricity supply will be reduced over time as renewable energy production is deployed.

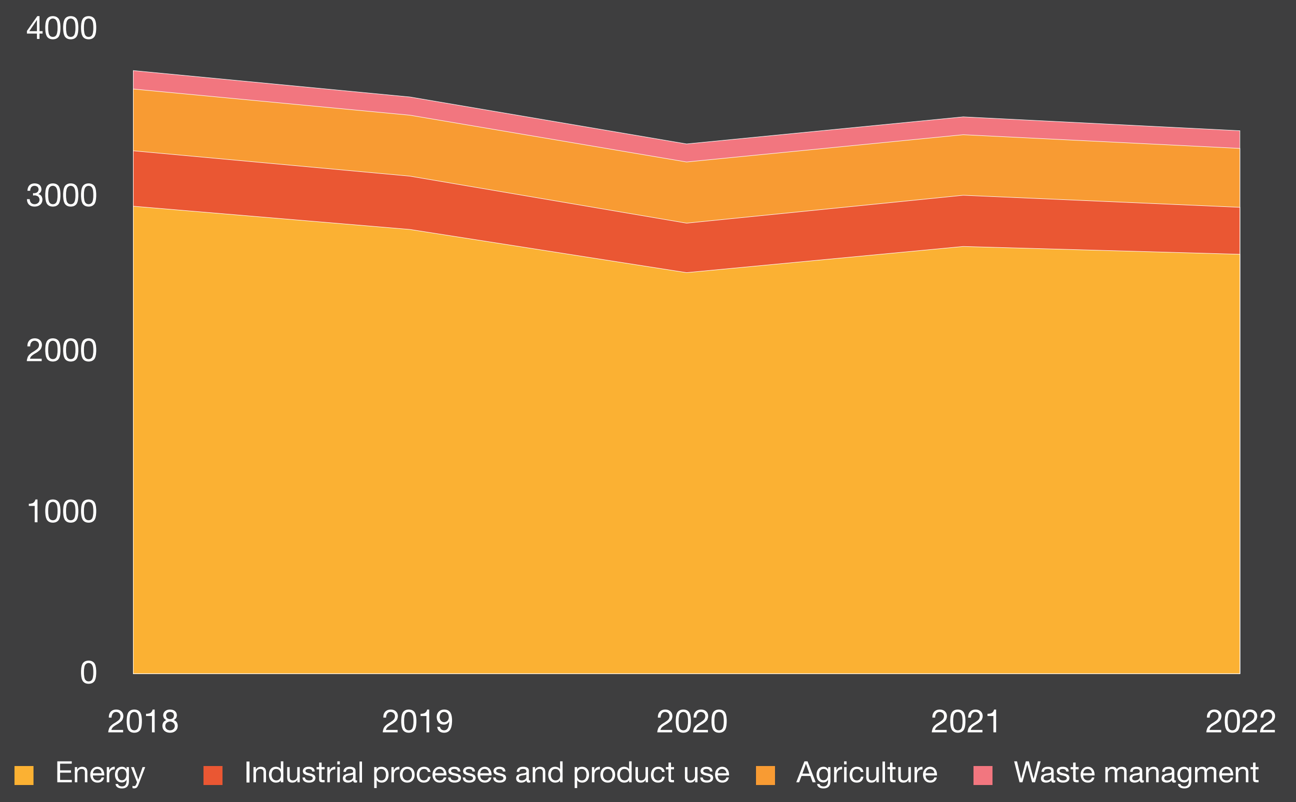
Some sectors, such as aviation, shipping and iron and steel production, cannot be directly electrified as easily and are known as hard-to-abate sectors[11,12]. In these cases, CCS and hydrogen, with its derivatives, become valuable options. CCS allows for the continued use of conventional technologies, but with the emissions captured and permanently removed. Hydrogen could substitute fossil energy use in several sectors.

The decarbonization of the European energy system thus rests upon three pillars: renewable electricity production and electrification, carbon capture and storage, and low-carbon hydrogen production. As shown in this report, the North Sea can contribute to all of these solutions through its high potential for offshore wind and vast capacities for CO_2 sequestration, both of which enable large scale production of low-carbon hydrogen.

Two thirds of EU's energy supply in 2022 was from fossil fuels[8]



EU's greenhouse gas emissions are concentrated in the energy sector[9]



Clean electricity is a cornerstone of European decarbonization

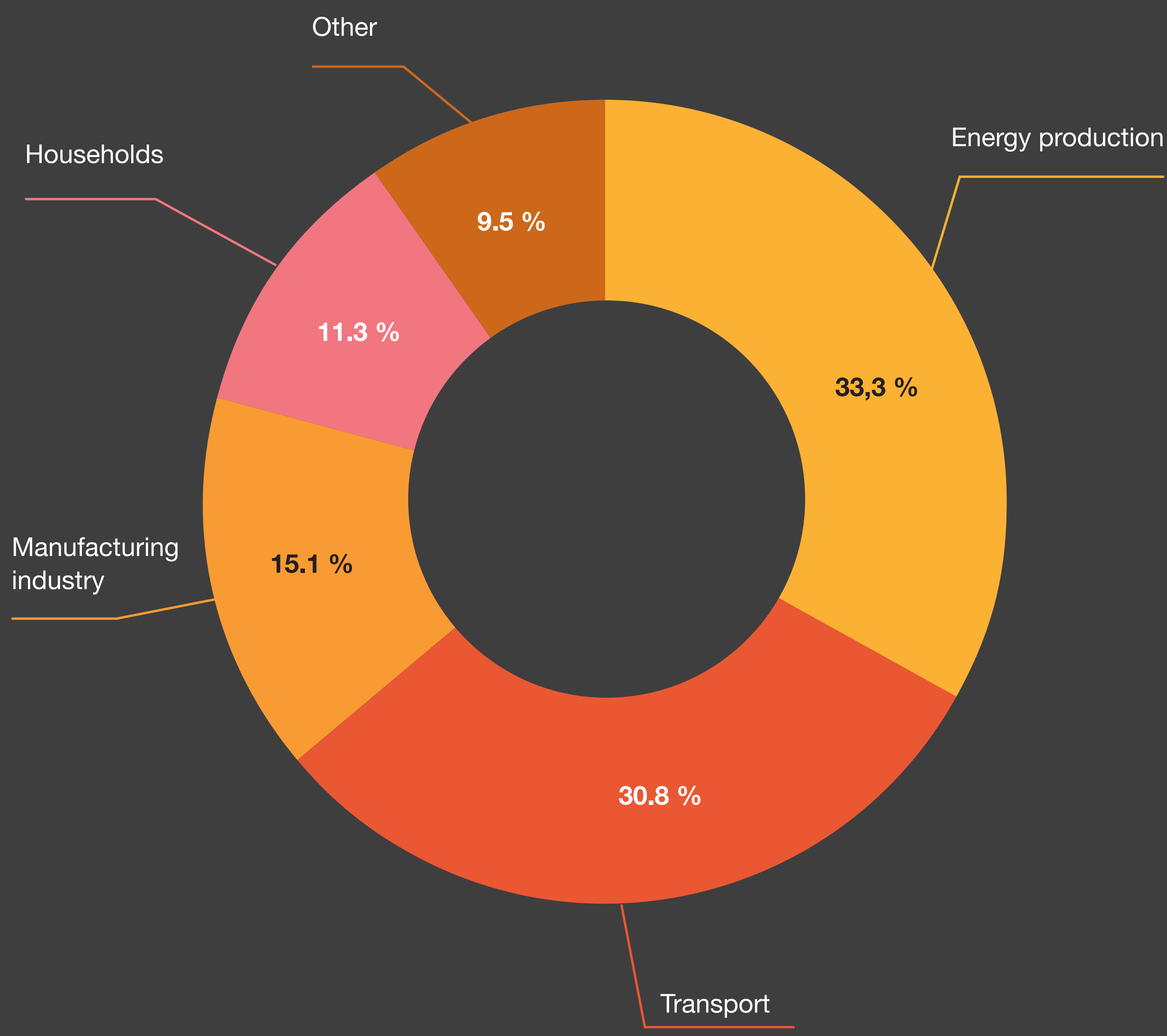
Consumption of energy accounts for the largest share of the emissions of greenhouse gases in the EU today, accounting for almost 80% of all emissions[8]. Currently, the most significant source of greenhouse gas emissions is the production of electricity, closely followed by the use of fossil fuels in road transport.

Simultaneously, the demand for electricity is rapidly changing. A central strategy in Europe to reduce emissions involves replacing direct fossil energy use with electrification[10,13], where transport and industrial processes are to be electrified. Moreover, the EU has set a goal of 10 million tonnes of renewable hydrogen production in the EU by 2030, with an additional 10 million tonnes of renewable hydrogen imported from neighboring regions[6]. This will further stress the European power sector.

This means that there are two main challenges for the European power system:
i) the current power generation capacity must be replaced by renewable and low-emission energy sources; and
ii) the total demand for electricity will significantly increase in the future as additional sectors are electrified and new green industries mature across Europe.

To decarbonize the electricity supply, the EU has set a target that at least 42.5% of all electricity consumption should be met with renewable energy in 2030, with an aspiration that this share should be 45%[14]. Beyond this, the EU has also set explicit targets for investments in specific technologies, including 60 GW of offshore wind by 2030, and 300 GW by 2050 across Europe[15]. The member states have subsequently raised their ambitions for 2030, and now target 111 GW of installed offshore wind capacity by the end of this decade[16].

Transport and energy production were the largest sources of greenhouse gas emissions in the energy sector in 2022[8]



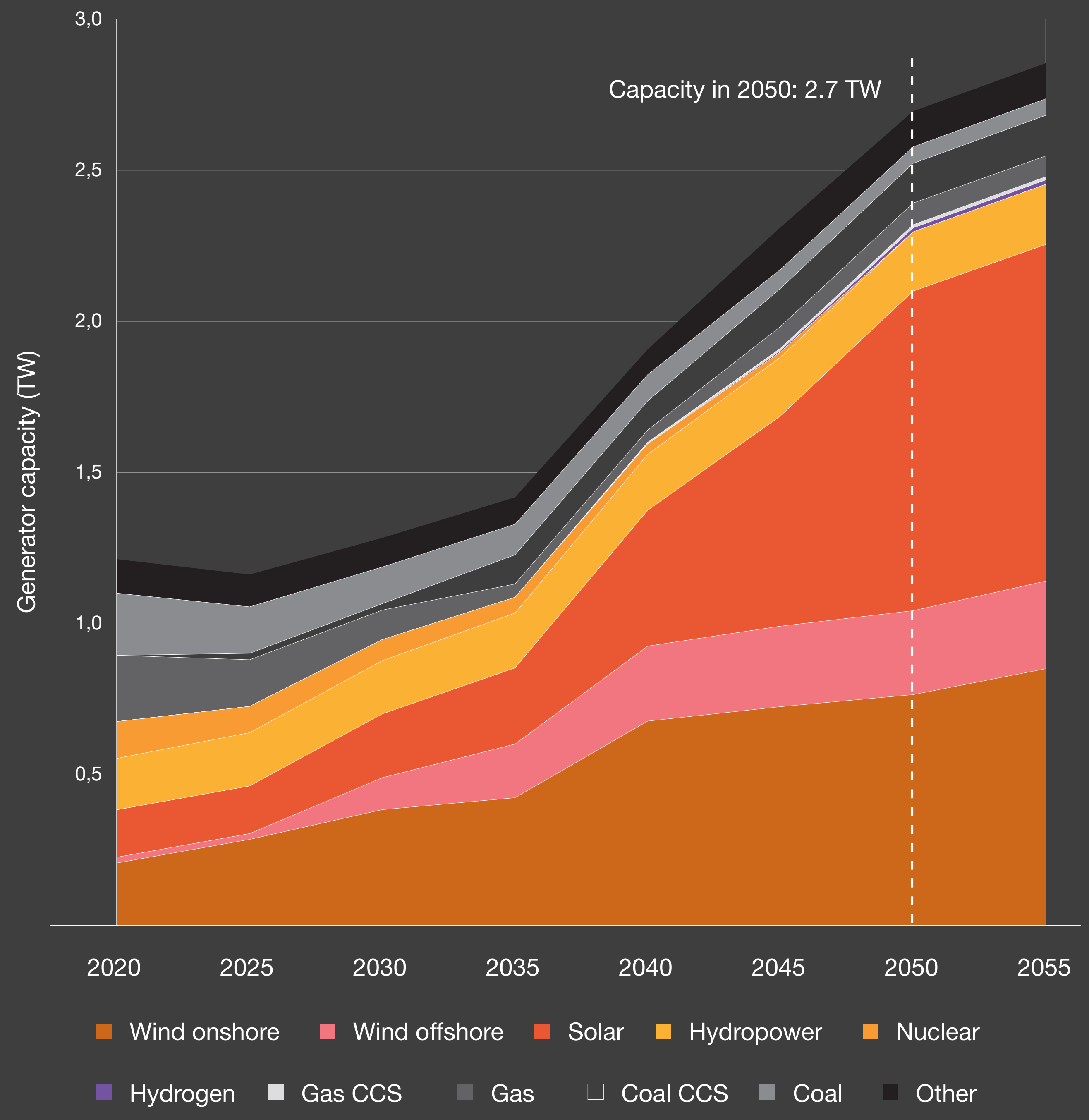
Renewables will be the dominant source of energy by 2050

In the transition towards cleaner energy, the share of renewable power generation will increase significantly. In 2022, renewable energy sources accounted for 41.2% of gross electricity consumption in the EU[18]. By 2050, the share of renewable power generation capacity will grow to over 85% to sufficiently decarbonize the energy system and reach net neutrality in the wider energy system. The largest increases are expected to be in solar photovoltaic capacity, followed by onshore wind power. Offshore wind will also play an important role in the decarbonized power system, serving the coastal regions with additional and more reliable renewable energy.

The remaining sources of electricity in 2050 are composed mainly of dispatchable power generators, which can include nuclear generators, or those fuelled by gas, coal or hydrogen. The exact prospective power mix depends on future technology development, regulatory frameworks and international trade developments. Our analysis suggests that coal can play an important role in the future, owing to the wide availability within Europe, but is strongly influenced by the availability of natural gas in the European energy system. This power production is mainly used to secure electricity supply when the renewable sources are unable to meet the electricity demand.

CCS would play an important role when using fossil fuels[19]. While using unabated fossil energy is irreconcilable with the climate targets, the use of fossil fuels in combination with CCS allows these generators to play a role in the decarbonized power system. In this way, these power generators complements the renewable energy sources by securing the supply of energy, while implementing measures to ensure that the climate targets set by the EU are reached[20].

EU's power system will primarily be decarbonized through renewable energy[17]



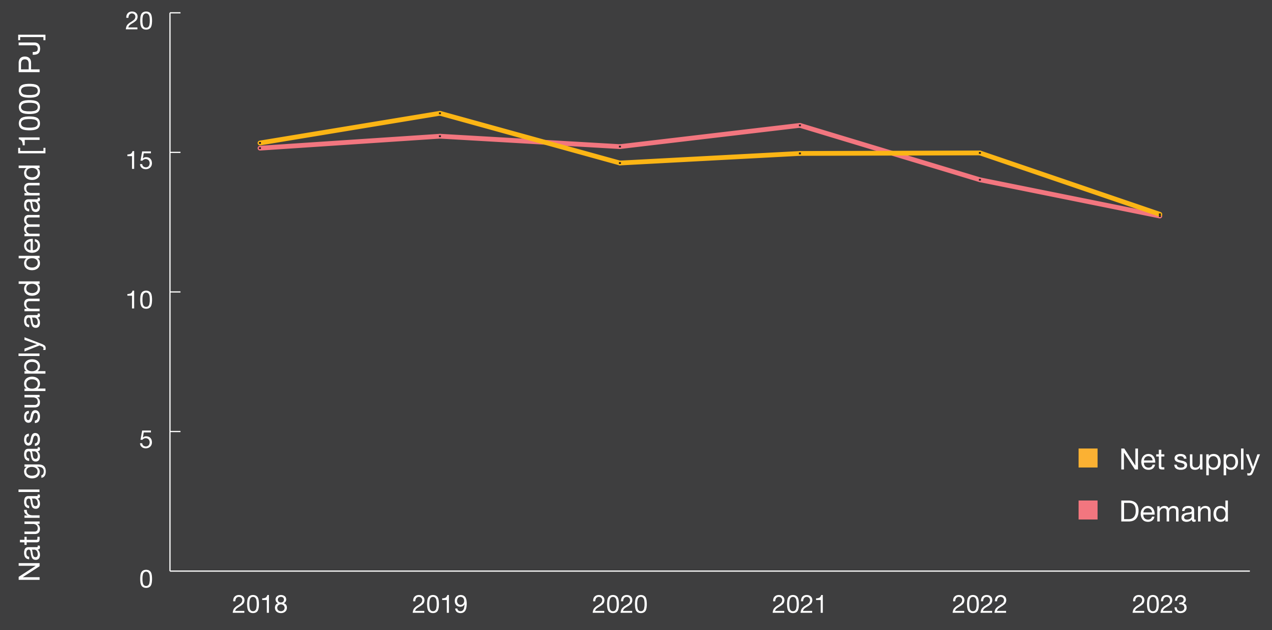
Natural gas will play a smaller role in the power system than before

The European energy system experienced a shock in 2022, when Russia's natural gas supplies were abruptly cut. This significantly changed the outlook of the development of the European energy system. Whereas gas used to be considered a key resource in both the power system and the broader energy system, today its future role in the power system is considerably reduced according to our analysis. Given that the access to natural gas has been reduced in Europe, it has become more important to prioritize its use in the areas where it is most valuable.

The difficulty with phasing out natural gas from a certain sector depends primarily on the alternatives that can substitute its use. The power sector, for example, has several options readily at hand to replace natural gas use, including other increased renewable production and other fossil fuels. In other sectors such as the petrochemicals industry[13], natural gas is a necessary feedstock, and cannot be replaced as easily.

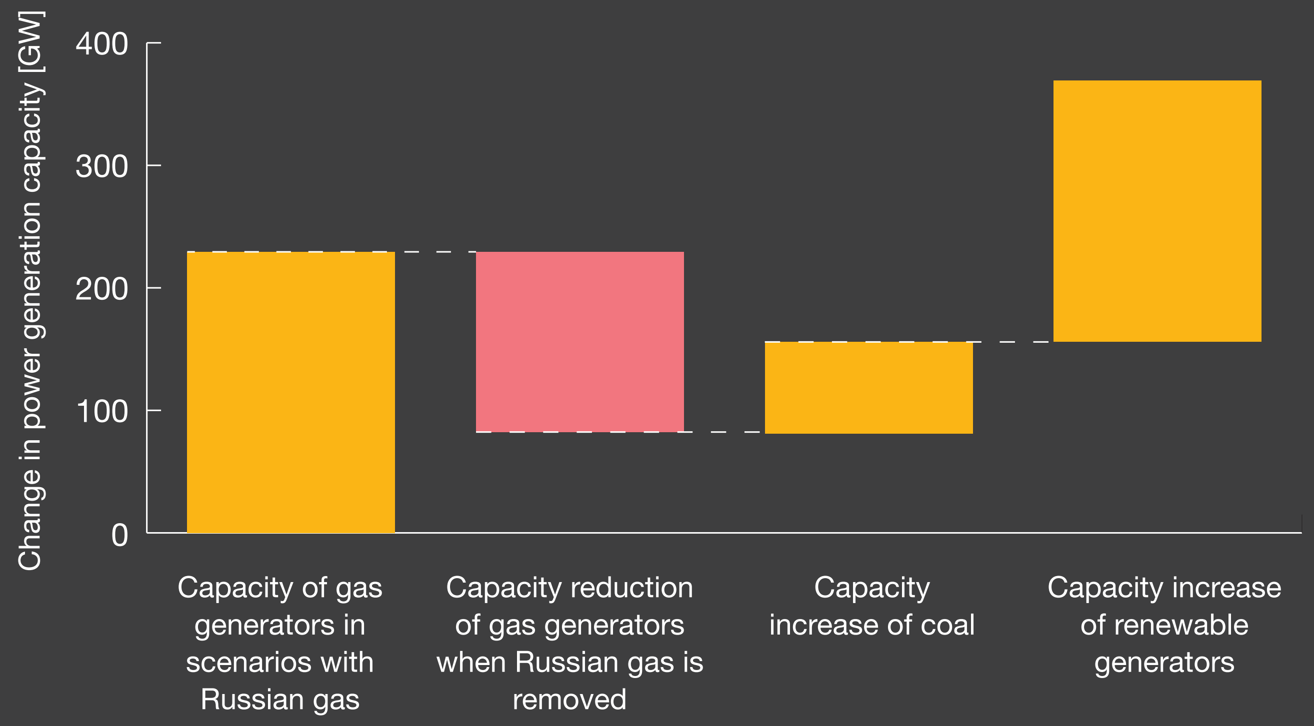
The substitution of natural gas in the power sector is seen in our results, and the pivot towards renewables is also observed in other similar reports[13,23]. It is clear that substituting natural gas with renewables in the power sector is an economical pathway to ensure energy security in Europe. For the power system, it is also important to replicate the balancing capabilities of natural gas power plants as natural gas is phased out. One option is to continue using coal as a fuel to produce electricity when renewables do not produce sufficiently as seen in our results. Other options are also available, including nuclear power or producing and storing hydrogen from excess renewable electricity, and using this as a fuel to secure adequate power supply.

EU's natural gas supply has been reduced significantly following the Russian invasion of Ukraine, while consumption has not fallen proportionally[21,22]*



* Net supply is the sum of indigenous production and import, with export removed

The use of natural gas in the power system will be significantly reduced by 2050 due to its scarcity in Europe[17]



The North Sea can ensure that the EU reaches its offshore wind targets

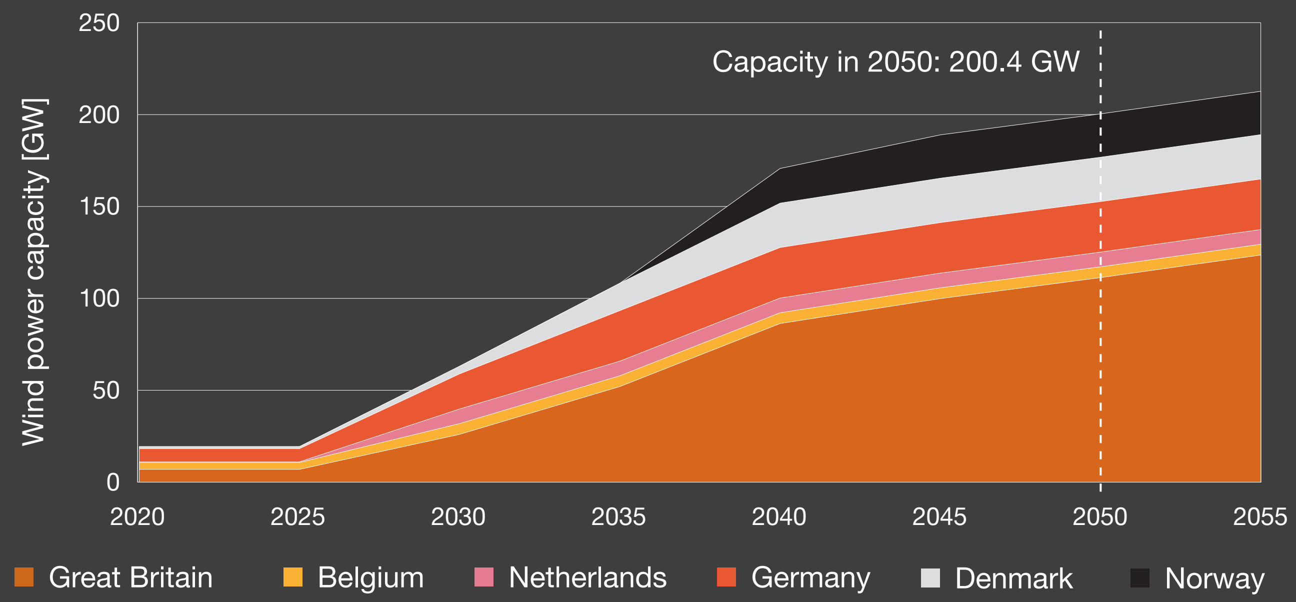
Offshore wind in the North Sea has a tremendous potential to contribute in reaching the European offshore wind goals, and by 2050 we predict that 200 GW can be installed. This is in line with the findings by Wind Europe[25], reporting that the North Sea can install 212 GW by 2050. Offshore wind can be developed in all areas of the North Sea, with Great Britain taking a large share as a result of opening large areas for wind power development. We predict that the potential for offshore wind in the North Sea will increase as more offshore areas are made available for development.

This potential will not materialize without close collaboration between the North Sea countries. An important characteristic of offshore wind in the North Sea is that it is critical to deliver the generated power to the location where it is most needed. It is therefore important to develop the electric grid in the North Sea, and allow for hybrid connections between the wind parks. In this way, the North Sea grid will have sufficient flexibility to consistently route the power to the highest priority regions. This increases the value of North Sea offshore wind significantly, as seen in the bottom Figure.

The phasing out of Russian gas from the European energy system, and the accompanying energy scarcity, also increases the potential of North Sea offshore wind, and may lead to additional investments by 2050. This is significant, but the largest increase comes from international collaboration.

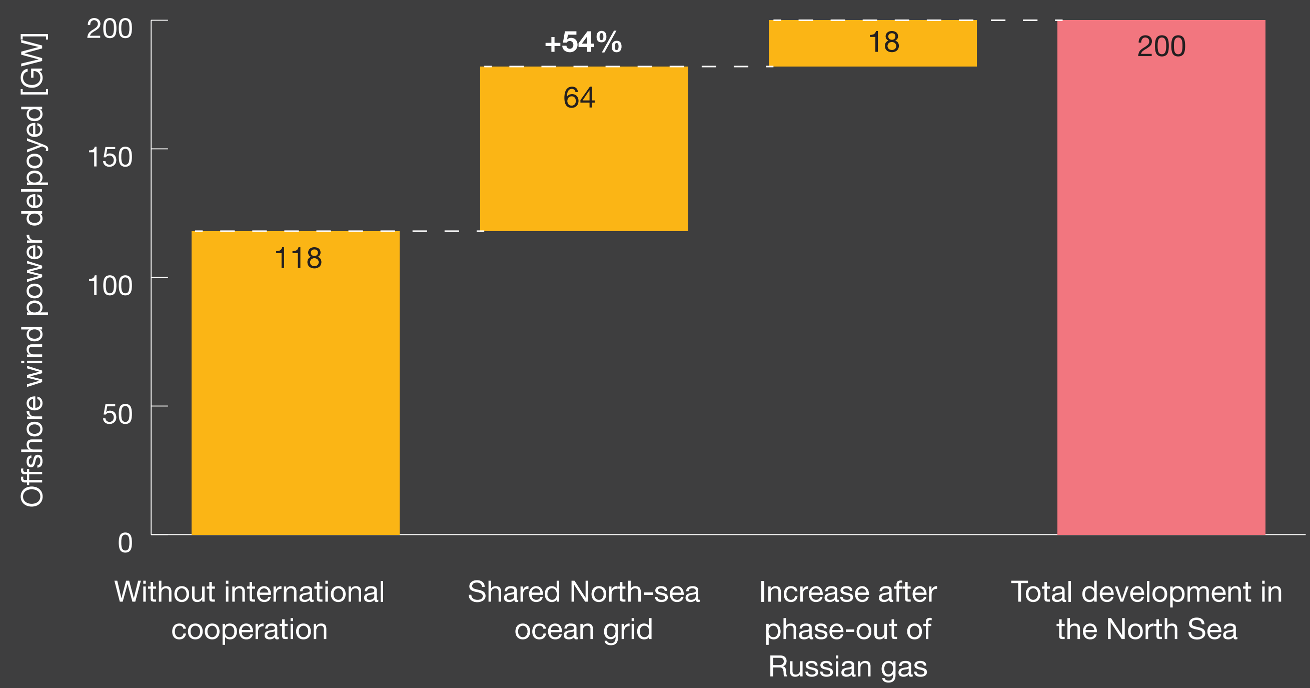
Europe also has a potential to develop offshore wind in regions other than the North Sea, including the Mediterranean Sea, the Baltic Sea, the Norwegian Sea and the Atlantic Ocean off the coast of Ireland. The potential for development in these regions have not been studied here, but is likely significant as well[25].

The potential for offshore wind is high, especially in the UK[17]*



* Offshore wind areas that were recently opened for development off the coast of the Netherlands are not included in this study. The Dutch capacities used in this study are fully utilized.

International cooperation is critical to unlock the potential of offshore wind in the North Sea[17,24]



The realization of the North Sea's offshore wind potential requires international cooperation

Unlocking the potential of offshore wind in the North Sea will require substantial investments in the grid. In early developments, it is sufficient to connect the wind parks domestically via radial connections. However, in the longer term, it will be necessary to allow for hybrid connections between the wind parks. This will ensure that the energy produced can be routed to where it is needed, and thereby avoid curtailment of renewable energy.

Other than hybrid connections, it is also possible to coordinate energy infrastructure development through energy hubs, or islands. The benefits of energy hubs are that they are centralized and share infrastructure, which may reduce costs for each individual offshore wind project. It is also possible to place electrolyzers within energy hubs, thereby allowing for new uses of offshore wind power that further increase the value of the energy.

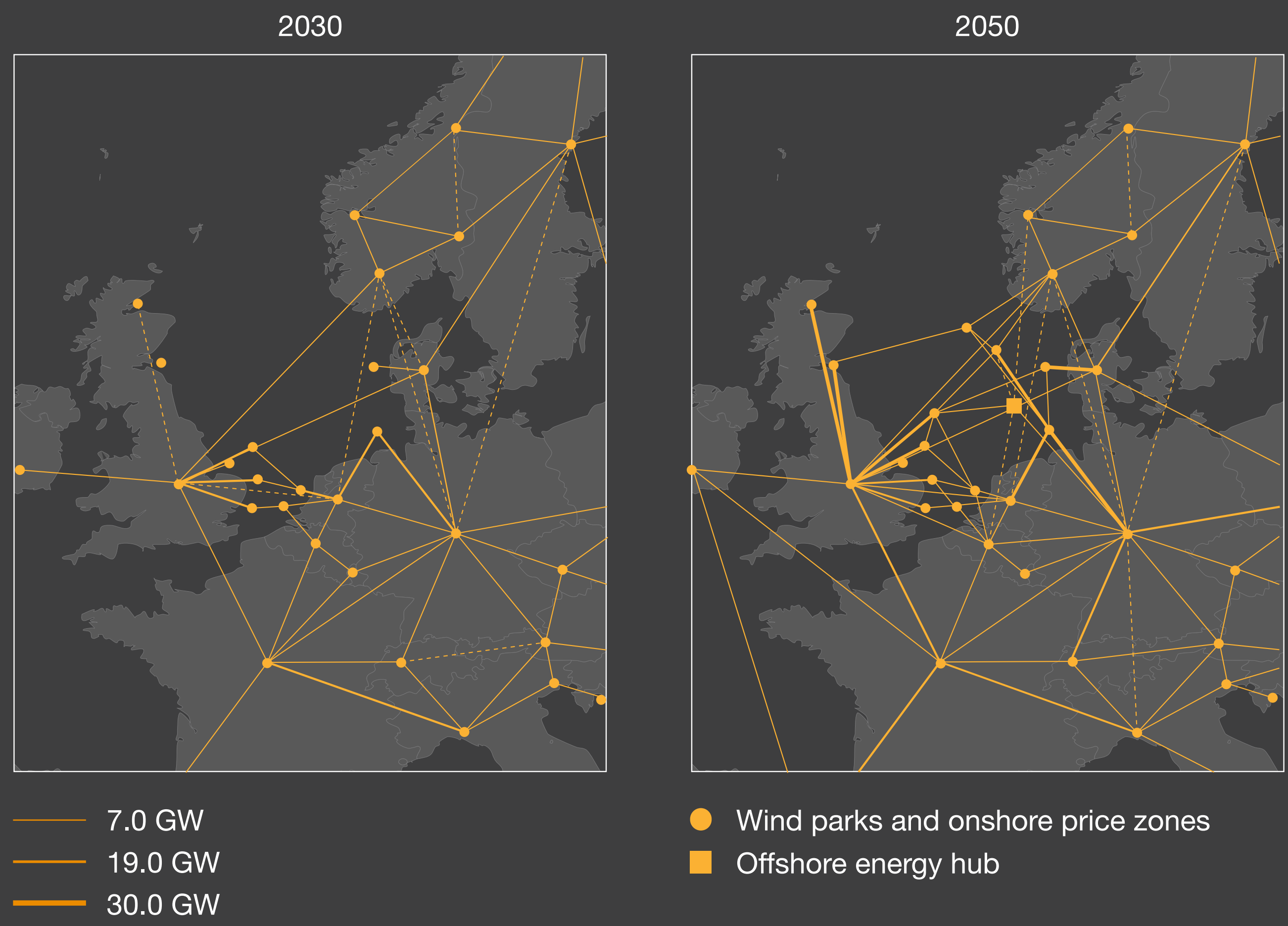
Explanation: Energy hubs

Energy hubs are man-made constructions that serve as common infrastructure for offshore wind parks in a given region, such as the North Sea. The primary function of the energy hub is to reduce investment costs of the offshore grid by allowing several wind parks and countries to connect to a single point, rather than all the individual wind parks.

Energy hub concepts also typically feature electrolyzers that enable hydrogen production offshore. This may be a cost-effective way of producing green hydrogen[26], especially if using excess renewable power. Some concepts also feature hydrogen storage that allow for buff-ering of hydrogen for when it is needed. It is possible to transport the hydrogen to shore via pipelines or through ships.

Denmark is at the forefront of the development of energy hubs, and have committed to building one artificial island in the North Sea and one in the Baltic sea. These will connect to offshore wind parks in the two regions, and allow for transmission of electricity to the Danish grid. There is also an ambition for the energy islands to produce hydrogen for the Danish and European markets[27].

The North Sea grid will need to be closely integrated with hybrid connections in order to realize the potential of offshore wind, and will need to develop gradually over time[17]



Carbon capture and storage is an important technology in the energy transition

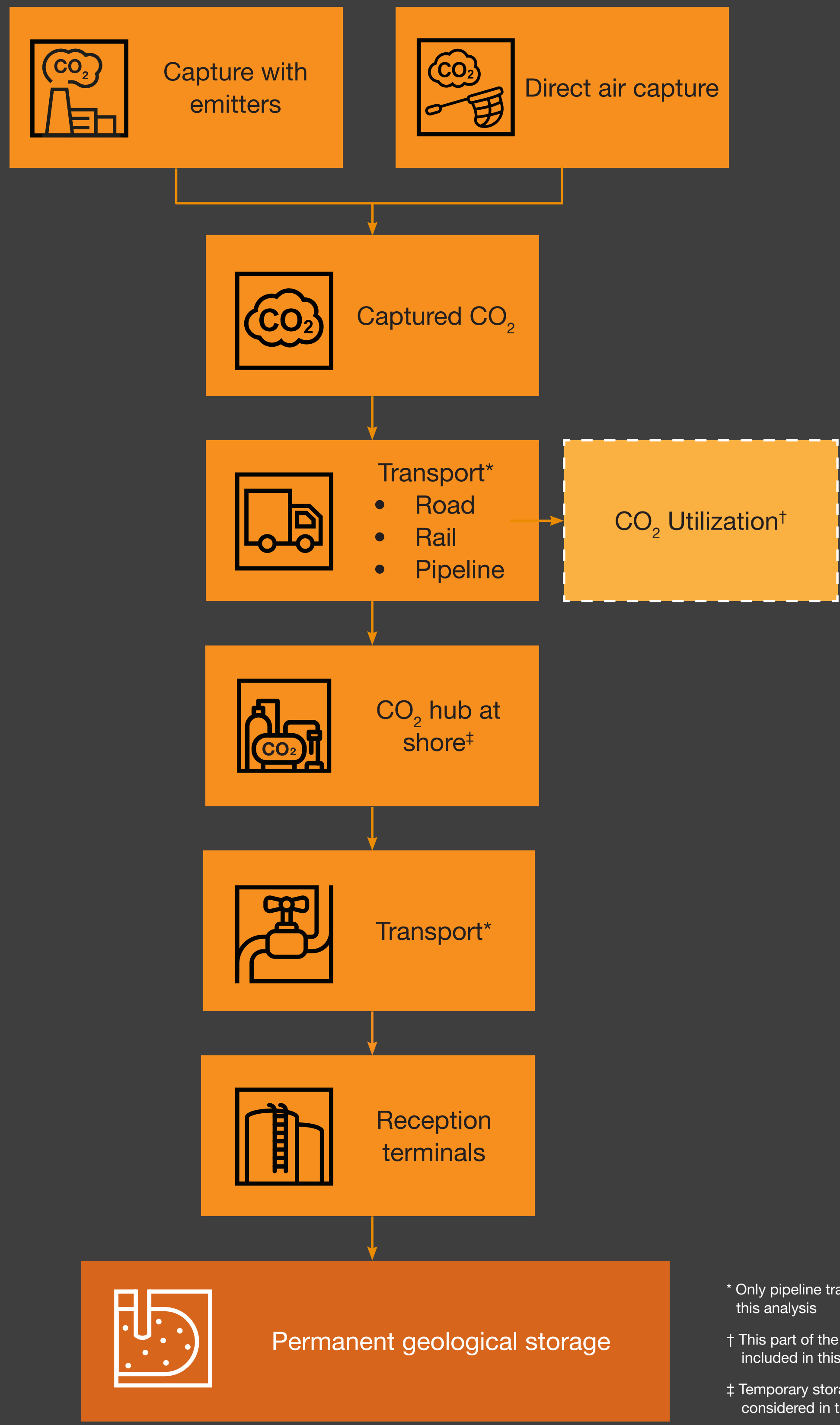
CCS is one of the ways through which we can reduce CO_2 emissions in our energy system, and is anticipated to play an important role in global decarbonization[23,28]. CCS involves using various technologies to capture CO_2 either at the source of emissions or from the air. This captured CO_2 can be reused in industrial processes, or it could be transported for permanent geological storage. In this way, CO_2 that would otherwise be emitted to the atmosphere, is instead either recycled or removed altogether.

The EU recently published a strategy describing the role of CCS in the decarbonization of the European energy system[29]. Herein, the European Commission propose that 50 million tonnes of CO_2 should be permanently stored by 2030 annually. The role of carbon capture is further expanded by 2050, where they suggest that 450 million tonnes of CO_2 should be captured, of which roughly half can be reused in industry.

CCS is most suited to sectors that produce large emissions, in which switching the fuel to green alternatives is either difficult or leads to limited reductions of greenhouse gas emissions. Such sectors include the cement industry and steel industry[30]. Where current hydrogen production is largely based on natural gas reforming with considerable emissions, CCS may reduce up to 95% of the emissions, thereby opening for low-carbon hydrogen that may be used to decarbonize other industries.

CCS may also be used to reduce the amount of CO_2 in the atmosphere, using either direct air capture (DAC) or bioenergy with carbon capture and storage (BECCS). With DAC technology, CO_2 is captured directly from the atmosphere, and could be permanently stored. BECCS combusts biomaterial, which has consumed CO_2 during plant growth, and when the CO_2 is captured and stored following the combustion, then the total CO_2 amount in the atmosphere has been reduced.

Overview of the CCS value chain



* Only pipeline transport is considered in this analysis

† This part of the CO2 value chain is not included in this study

‡ Temporary storage of CO2 is not considered in this analysis

The power sector has a high potential for CCS. Hydrogen production and industry can also drive CCS growth

CCS may play an important role in the decarbonization of Europe, but it requires that governments establish clear regulatory frameworks that encourages its commercial development. At the same time, private companies must also invest in the facilities for capturing, transporting and finally permanently storing CO_2.

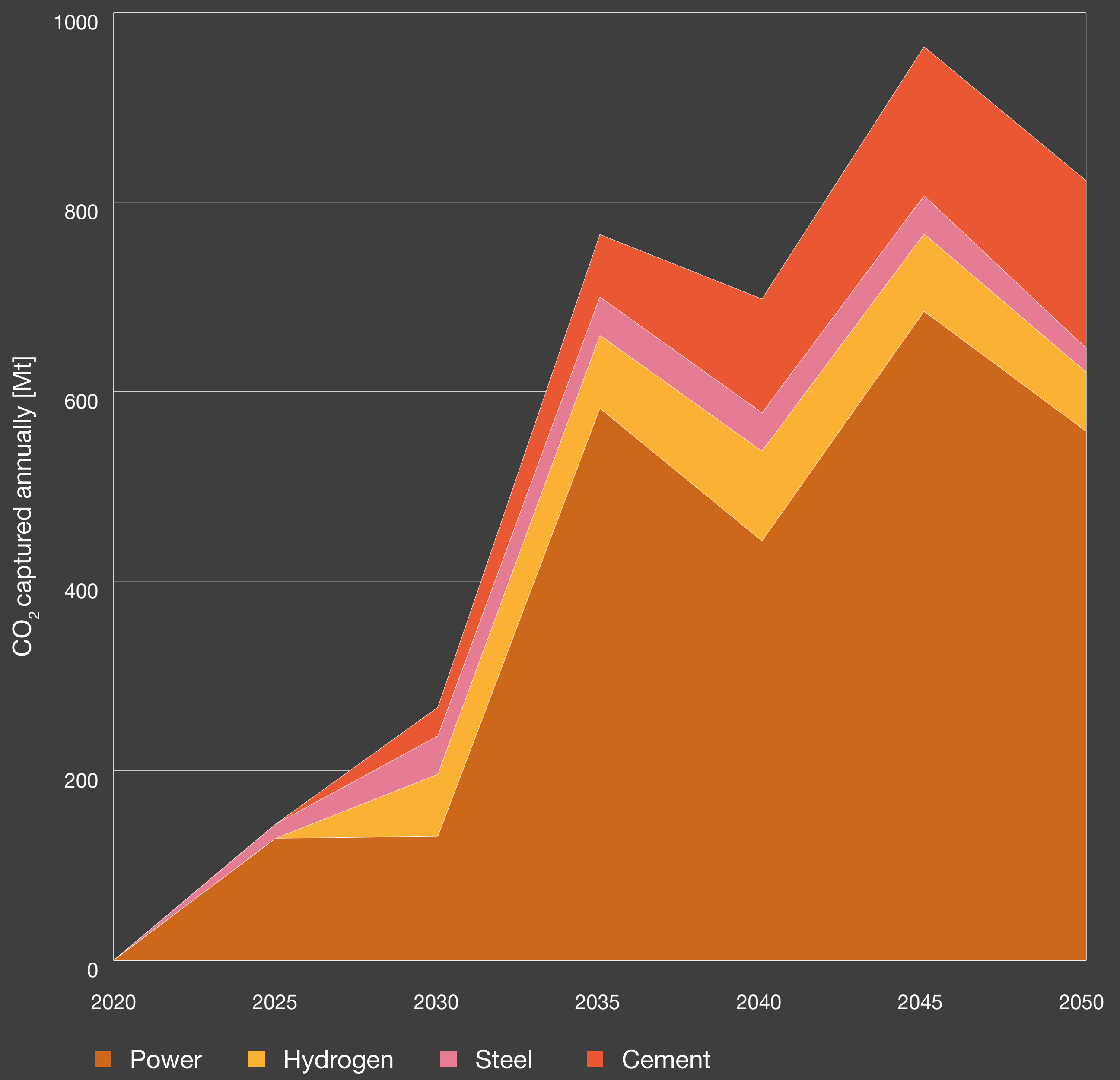
In this effort, we are behind schedule. The economic potential of CCS is present already in the power sector, which turned to coal in 2022 to face the climate crisis[31]. It is difficult to precisely define how big this potential is. During the energy crisis, Europe aggressively deployed renewable power production, and electricity demand was reduced considerably[32], particularly in the industrial sector. This has in turn led to less coal and gas use in the power industry than previously predicted. How the electricity demand develops as energy-intensive industry is restarted will be key for the potential of CCS in the power sector in the near term.

In the longer term, the potential for CCS in the power sector increases considerably. There are two main drivers for this:

- **An overall increase in the electricity demand increases total power generation needs.** The total electricity demand in Europe is predicted to increase considerably. Most of this is can be met with renewable generation, as seen in Figure on page 15 that shows development of power generation in Europe. However, some of this demand can also be met by fossil generators with CCS.
- **Large shares of renewable power requires considerable balancing capacity.** As the European power system relies more on renewable production, it will also be more exposed to inadequate supply when the renewables produces insufficient energy. Dispatchable generators, such as fossil generators with CCS, will have to compensate for the renewable production shortfall.

Beyond the power sector, it is evident that CCS has a considerable potential in hydrogen production if this is produced using natural gas, and in the cement and steel industries. The potential in the steel industry is limited, given that steel can be decarbonized using hydrogen in the long term as this technology matures. Unlike the steel industry, cement production cannot be fully decarbonized with a fuel switch to hydrogen, and consequently, the potential for CCS in this sector remains high throughout the investigated timeframe.

The power sector may be an early adopter of CCS, and could utilize CCS at large scale in the foreseeable future[17]



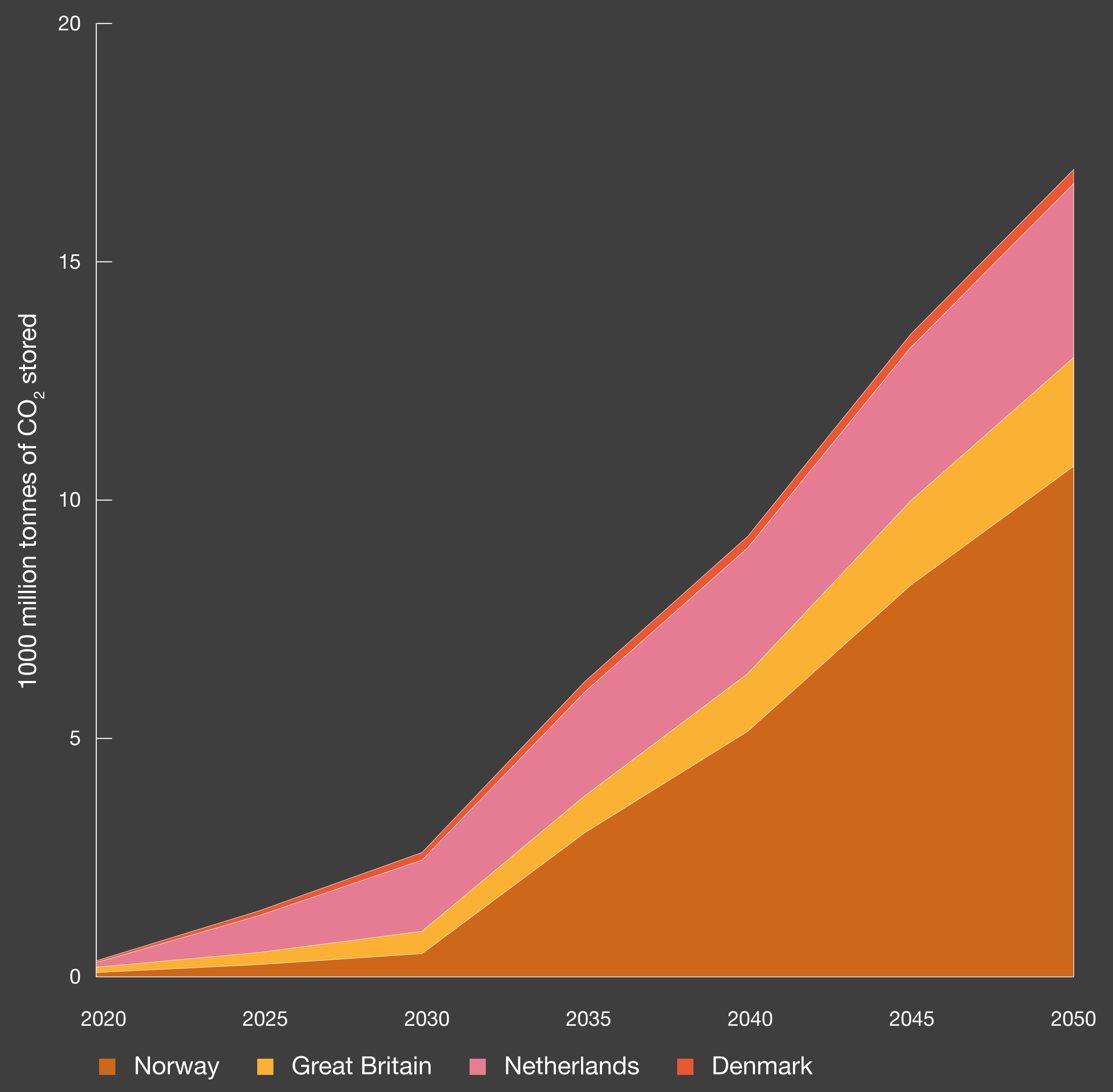
Norway's potential for offshore storage of CO_2 is uniquely large

The permanent storage of CO_2 in Europe has historically favored offshore storage, and the North Sea has dominated as the preferred location[33]. Our analysis shows that the North Sea has a considerable potential for storing CO_2 captured in Europe. Over 15 billion tonnes of CO_2 can be economically stored in geological formations in the North Sea by 2050, with the available capacity being considerably higher.

Early movers in this space include Denmark and the Netherlands, who are initially preferred owing to their geographic proximity to major emitters in continental Europe. However, their capacity for storing CO_2 offshore is limited. As a result, Norway, with its larger capacity for storage on the Norwegian continental shelf, has the potential to become the largest actor in offshore CO_2 sequestration in Europe. By 2050, Norway may permanently store over 10 billion tonnes of CO_2, more than 200 times the annual greenhouse gas emissions in Norway today.

Several countries, including Denmark, France and Poland, have begun exploring the potential for onshore CO_2 sequestration. This is predicted to be less expensive than offshore sequestration, and may be initially favorable. The success of onshore storage depends on regulatory conditions allowing for this technology, social acceptance and availability of storage sites. If these conditions are met, then onshore CO_2 storage may lower the potential for CO_2 storage in the North Sea, but may also simultaneously increase the demand for CCS in Europe due to lower costs.

Norway has an exceptional potential to store CO_2 offshore for Europe and can have stored 2/3 of the CO_2 in the North Sea by 2050[17]



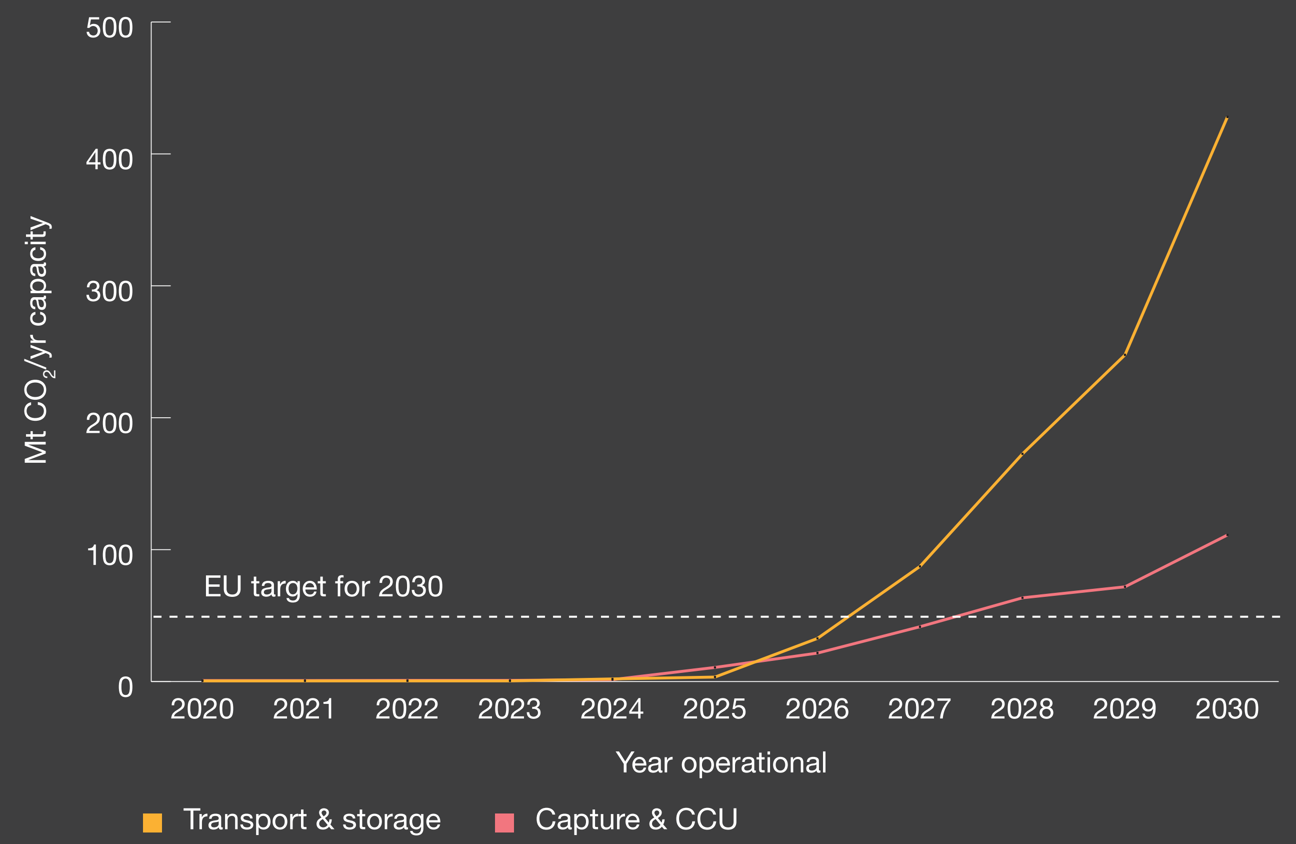
Europe is on track to meeting their CCS goals in 2030 if announced projects are realized

Europe has a few full-chain CCS projects in operation, with the CCS project on the Sleipner oil and gas field from 1996 being the largest, storing approximately 1 million tonnes of CO_2 annually. Altogether, there are six CCS and CCU projects in operation, storing or using just under 3 million tonnes of CO_2 per year. Most of these projects are in the oil and gas sector, where the CO_2 is captured either to i) meet the export requirements of natural gas, ii) increase oil production through enhanced oil recovery, iii) lower the environmental footprint of oil refining by producing low-carbon hydrogen.

The current CCS project pipeline is in line with the goals set by the EU, considering both the capture and transport and storage projects. If all projects are realized, then the CCS sector will realize more than double the amount of permanent CO_2 storage than the EU target. This would significantly benefit the realization of the net neutrality goals set by the EU. Should all projects not be realized, it would still be possible to reach the 50 million tonne per year target by 2030.

Currently there is a positive momentum in CCS projects driven by EUs Green Deal, Net-Zero Industry Act and EU Industrial Carbon Management strategy. But there is still great uncertainty as to whether the 2030 targets can be reached. It would require require a significant number of projects reaching final investment decision (FID) the next two years. Further improvements in regulatory framework and decrease in technology cost is a key success factor for achieving ambitions for both 2030 and 2050.

Currently, there are more projects in the pipeline for transport & storage than for capture of CO_2[34]*



* Planned, under construction & operational projects

Further regulatory and technological improvements are required to unlock CCS in Europe

Significant progress has been made in advancing CCS technologies and projects in Europe, but high costs of deployment and development remain a primary barrier.

Deployment and development costs

Capture technologies, infrastructure, and storage projects require substantial capital expenditures, particularly early-stage projects without economies of scale. R&D is essential for improving efficiency and reducing costs, but poses a significant financial burden, especially for smaller firms and new entrants.

Navigating the regulatory and compliance landscape involves costly and time-consuming processes to meet stringent environmental and safety regulations, adding to legal and administrative expenses. Fluctuating carbon prices and potential policy changes create economic viability and uncertainty, discouraging private investment and necessitating public funding and subsidies to mitigate financial risks.

Infrastructure

Development of transport infrastructure including pipelines, compression stations, and monitoring systems for CO_2 transport requires significant planning and construction efforts. The current lack of CCS storage capacity hinders project development, leading to increased costs, project delays, and limited geographic reach. These challenges require substantial investments, streamlined regulatory processes, cross-border collaboration, and innovative financial mechanisms.

Market size

The current CCS market in Europe is relatively small but growing rapidly, with increasing interest in CCS as a climate change mitigation tool, and with many commercial-scale facilities in various development stages. Initiatives and funding mechanisms from the European Commission are accelerating deployment.

The North Sea is currently the primary location for CO_2 storage, with Denmark, Norway, the Netherlands, and the UK leading in policy and project support, and Bulgaria, Croatia, Greece, and Italy, developing projects in southeast Europe and the Adriatic Sea[33].

Public opinion and safety concerns

Impact on CCS Initiatives: Overcoming public opinion and safety concerns through engagement and education will impact advancement of CCS initiatives, reduce CO_2 emissions, and contribute effectively to global climate mitigation efforts.

Opportunities to improve the European CCS ecosystem

Addressing these challenges requires a coordinated effort involving substantial public and private investments, supportive policy frameworks, and continued innovation. With an estimated €12B needed by 2030, strategic funding and investment are critical to realizing the potential of CCS in mitigating climate change.

Regulatory Frameworks

Clear government policies, laws, and incentives are required to create a conducive environment for CCS deployment, providing certainty to investors and encourage private investment in projects. An example is the ETS, where emitters do not have to surrender allowances for captured CO_2, thus incentivizing development[35].

Technological Advancement

Continuous research and technological advancements and innovation improve CCS viability, reduces cost and improves overall efficiency. The current focus is on post-combustion capture, direct air capture, and novel materials for better CO_2 absorption.

Industry Engagement

Collaboration between project developers, energy companies, manufacturers, industry and other stakeholders accelerates technology development, operational best practices, and adoption. Furthermore, industry players can leverage outcomes of investments by leveraging expertise and resources, including repurposing existing oil & gas infrastructure for CO_2 transport and storage.

Public Acceptance

Raising awareness and garnering public support to dispel misconceptions, and foster support are important to enable informed policy decisions and project approvals, and social legitimacy for CCS projects.

Hydrogen will be central in the European energy transition

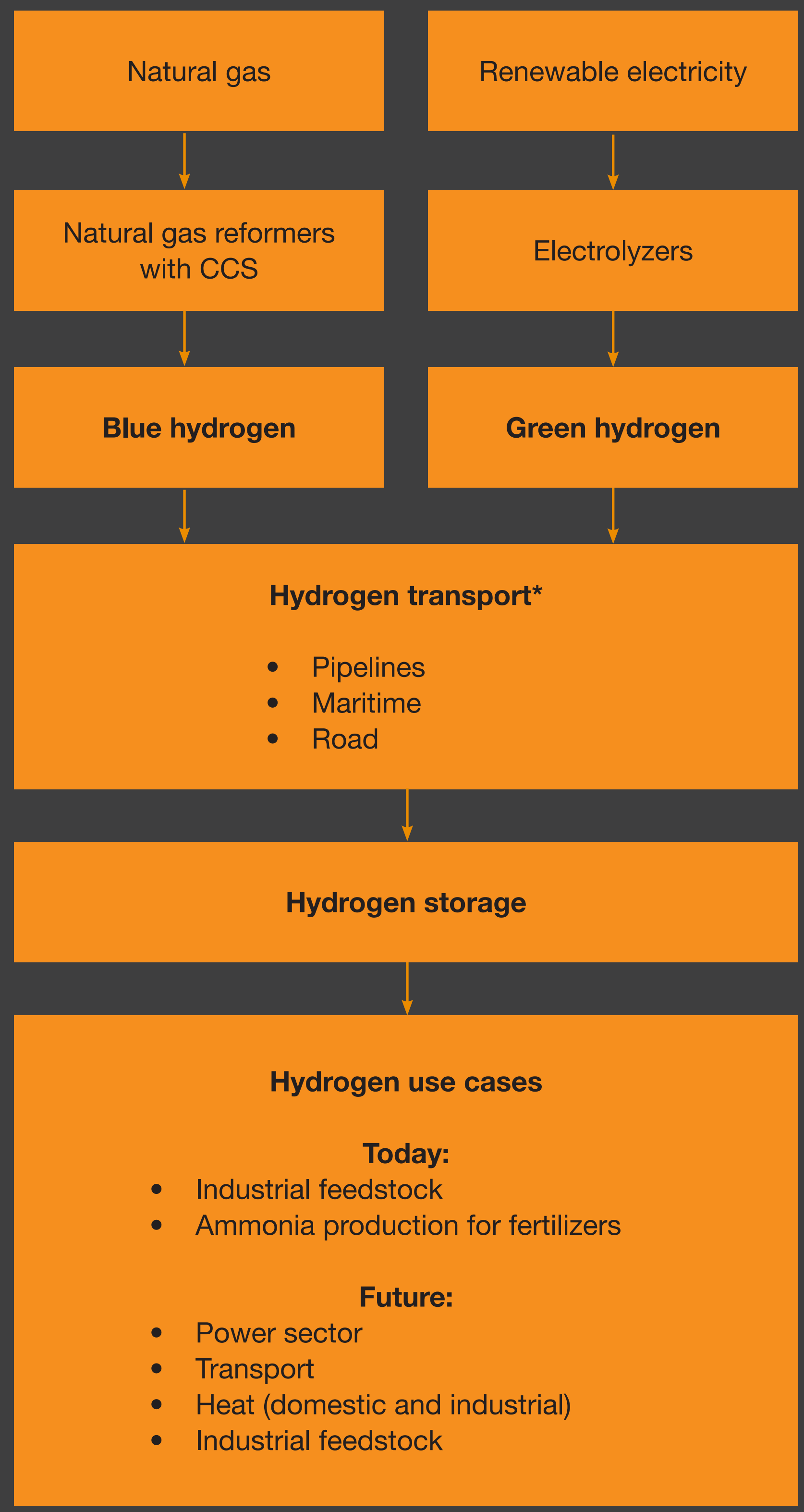
Hydrogen is a critical feedstock in several industries today, including the fertilizer and petrochemical industries. Supply mainly comes from natural gas reforming, which produces considerable CO_2 emissions[36]. The Figure to the right shows alternative production methods that yield low carbon hydrogen, and its uses in the energy system.

Hydrogen will become a central energy carrier in the future decarbonized energy system, and is being considered for several reasons:

- **Increases value of renewable energy:** Green hydrogen production can use excess renewable energy and hence increase the value of renewable energy sources[24]. This will be beneficial also for the hydrogen producer, as this energy will come at a very low cost.
- **Energy storage for intermittent renewable energy:** The production of electricity from renewable sources varies significantly between seasons. Green hydrogen has been proposed as an inter-seasonal storage of green energy, allowing for the consumption of renewable energy when the renewable sources do not produce enough[23].
- **Decarbonization of hard-to-abate sectors:** Some sectors are not able to decarbonize using only green electricity or carbon capture, such as intercontinental flight or long haul shipping. These sectors are reliant on hydrogen-based fuels in order to continue operations in a net zero energy system[23].

The EU has set a target of consuming 20 million tonnes of renewable and low-carbon hydrogen by 2030, where 10 million is to be produced in the EU, and the rest imported from neighboring regions[37]. Green hydrogen, i.e., hydrogen produced from renewable energy, is prioritized, but in the short and medium term, the EU acknowledges that other low-carbon sources will also be needed.

Overview of hydrogen value chain[36]



* Only pipeline transport is considered in this analysis

Both green and blue hydrogen will be important sources in a net zero energy system

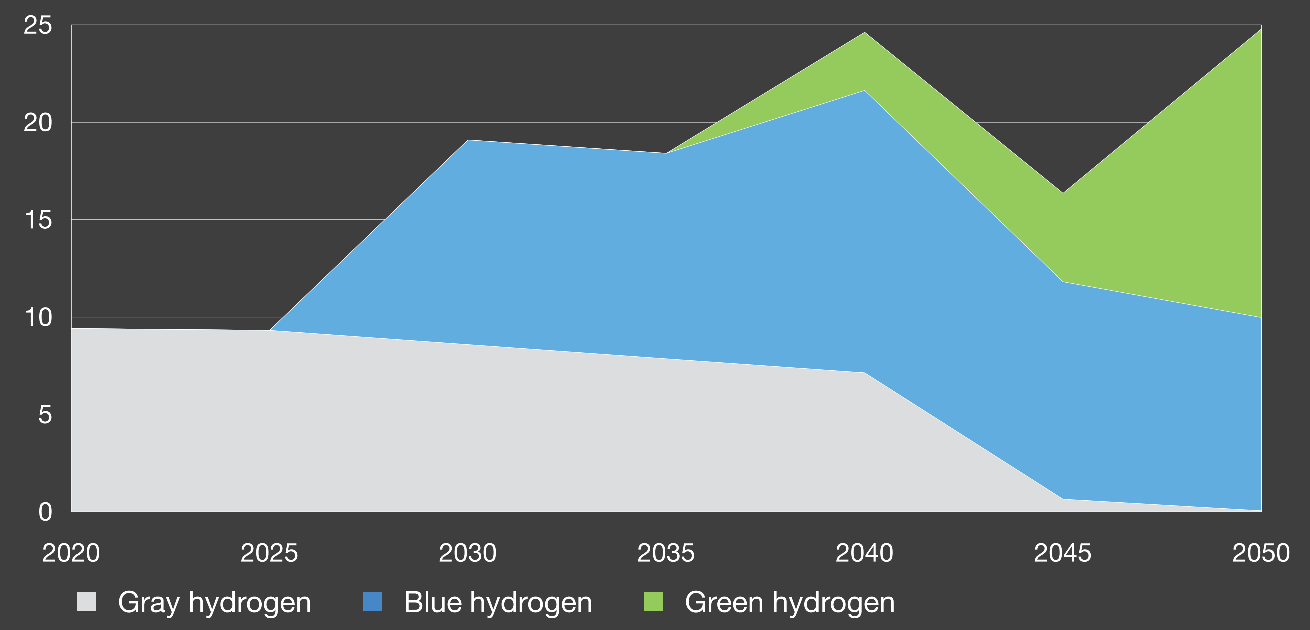
Unlike the production of fossil fuels and renewable energy, hydrogen can't be extracted from nature. Instead, it's produced using other energy sources, and when considering how hydrogen will be supplied in the future, it's important to keep in mind how abundant and accessible the required energy is. As shown previously, blue hydrogen uses natural gas as an input, whereas green hydrogen requires considerable amounts of renewable electricity.

When considering access to energy, in combination with the investment costs for the production plants[39] blue hydrogen appears to be a cost-competitive source of hydrogen both in the short and long term, as seen in the top Figure on the right. We therefore expect that blue hydrogen will be a key source of hydrogen, especially in the next decade.

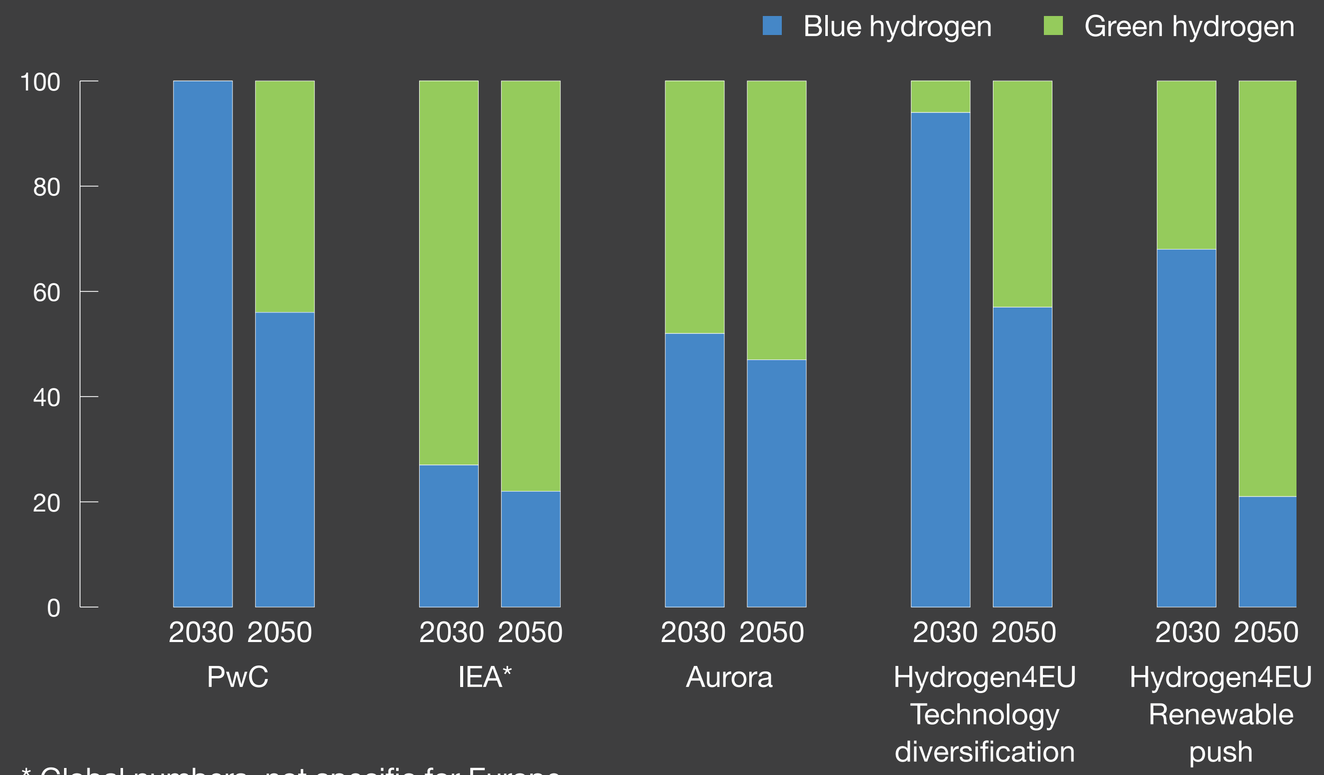
The primary reason for the delayed development of green hydrogen is access to renewable energy. Until the 2040s, we predict that the available electricity will be used in other sectors, limiting availability for green hydrogen production. There are however varying perspectives on this. The bottom Figure on the right shows different reports on the development of hydrogen supply, indicating how the predicted shares between green and blue vary depending on assumptions made. There are also reports showing how green hydrogen may supply all the necessary hydrogen in Europe[40], with a significant expansion of power generation in the electricity sector.

Certain sectors are reliant on hydrogen in order to reach the 2030 and 2050 targets. Our analysis shows that blue hydrogen can meet this demand cost-effectively, and at a large scale. In this way, blue hydrogen can bridge the gap between the need for economical hydrogen in the short term, and the unavailability of green hydrogen.

Blue hydrogen is the cheapest way of producing hydrogen until sufficient renewable energy is available[17]



The share of blue and green hydrogen in the European setting is highly uncertain, and different analyses arrive at varying conclusions[17,23,38,39]



* Global numbers, not specific for Europe

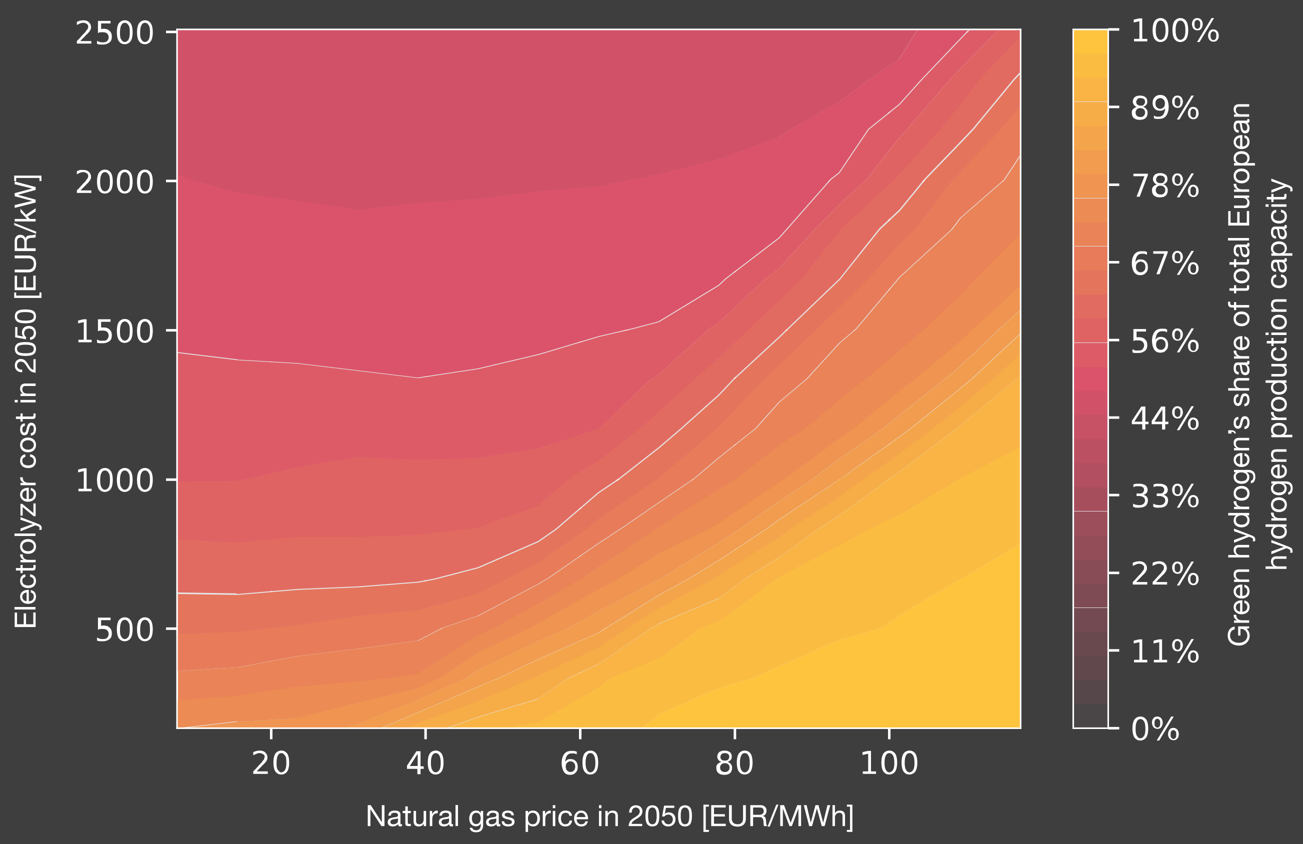
Green and blue hydrogen aren't competitors, and focusing too much on either can harm the hydrogen economy

Our analysis shows that in many future scenarios, both blue and green hydrogen will be key sources of supply in the European market. The demand for low carbon hydrogen will be high enough to sustain both means of production[41].

We predict that green hydrogen will account for the largest share of supply in 2050 in most scenarios. If the natural gas supply in Europe is tight, and the natural gas prices are high, then green hydrogen will dominate the supply, as the availability of low-cost natural gas is the most important prerequisite for cost-effective blue hydrogen production.

In order to realize the hydrogen economy, it will be necessary to use all available sources, and not only consider one way of production. Previous insights have shown that the focus on hydrogen "colors" may be stifling innovation and impeding the rollout of the hydrogen economy[42]. Central actors in the European market, such as the German government, have come to realize this, and have revised their strategy to also consider low-carbon hydrogen, rather than just green hydrogen[43].

Blue hydrogen is the cheapest way of producing hydrogen until sufficient renewable energy is available[41]



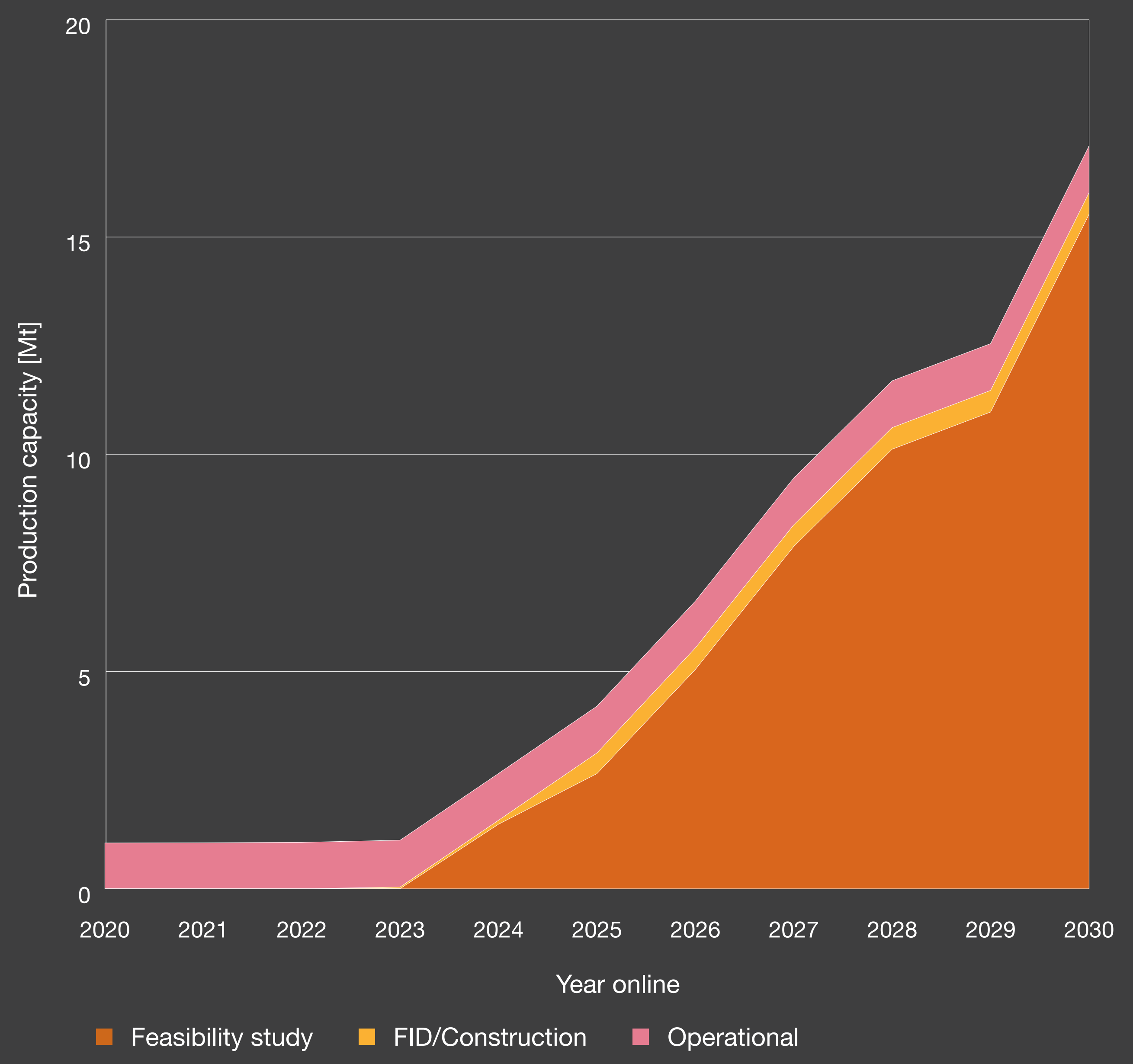
There is a gap between the EU goals and the project pipeline in Europe and neighbouring regions

Today, Europe is not on track for reaching its hydrogen targets. Reaching the 20 million tonnes of hydrogen production envisioned by the EU will require on average 3.8 million tonnes of hydrogen production additions each year until 2030. However, the project pipeline in Europe and North Africa, shown in the Figure on the right, demonstrates that the current project pipeline is not aligned with the EU targets.

Three important observations can be made in the project pipeline:

- **A very small minority of projects have reached FID or are under construction.** It is evidently challenging to mature projects to a FID. There are several reasons for this, but may generally be attributed to lack of available energy, an immature market for low-carbon hydrogen and lack of mature and commercialized technologies.
- **Most projects in the near future are only at a feasibility study stage.** Since it is challenging to mature projects, many developers choose to set their realization date into the future. In the meantime, it is possible that the necessary technology will mature further, lowering costs. Once a project is approved by the developer, it will take several years to build the production plant, meaning that if the projects are to be finished by 2030, then the developer must reach a FID in the near future.
- **Europe and its neighbors will still fall short of the target, even if all projects are realized.** The entire project pipeline in Europe and Northern Africa only amounts to 17 million tonnes of hydrogen production by 2030. If the EU is to reach the 20 million tonne goal, then either the EU will have to import from beyond its nearest neighboring regions, or facilitate an acceleration of projects domestically.

Very few hydrogen projects have reached FID or are under construction in Europe and Northern Africa[44]



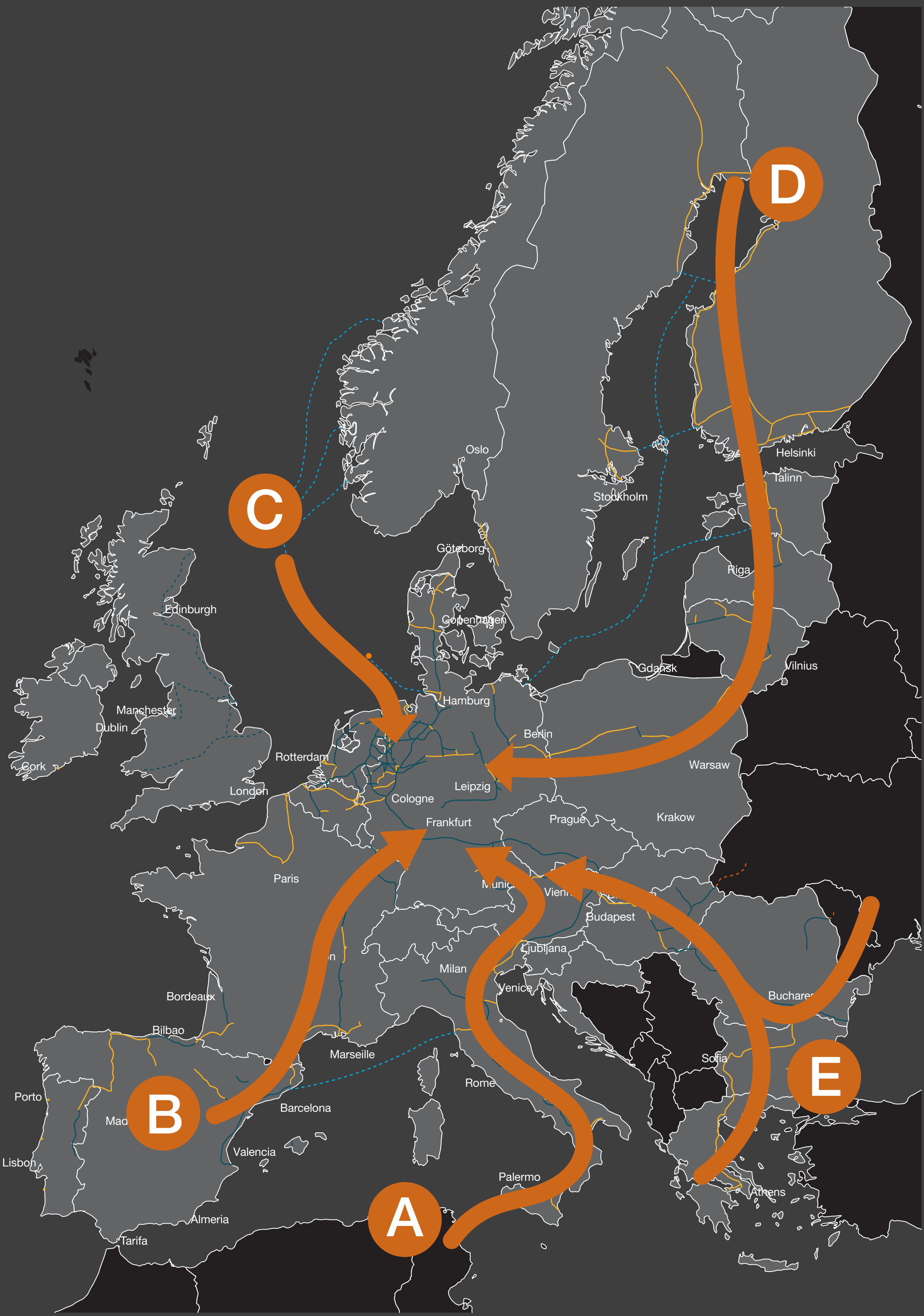
International cooperation is key to realizing the EU hydrogen strategy

International cooperation on hydrogen transport infrastructure will be critical in order to foster the hydrogen economy in Europe. The primary purpose of this infrastructure is to most efficiently utilize the advantages of each region, including the potential for low-cost production of hydrogen, or access to large storage capacities. Such cooperation would lower the cost of hydrogen to all consumers in Europe[45].

These regions are already connected through natural gas pipeline infrastructure. It is unclear how these pipelines will be utilized in the future, given the climate targets in the EU in the long term and the tightening of European natural gas supply in the short term. This infrastructure may be repurposed for hydrogen transportation, thereby saving on investment costs for infrastructure, while reusing existing assets. This would prevent stranded assets for natural gas pipeline operators, and ensure a more rapid and cost-effective deployment of hydrogen production and transmission.

Looking beyond Europe and its nearest neighbors, it may also be necessary to import from other regions as well. As seen previously, the current hydrogen production project pipeline in these regions does not meet the targets set by the EU. Imports from other, more distant regions may be the answer[39,42]. In the future, the EU may thus be importing hydrogen from the global market, much like liquid natural gas (LNG) today.

The hydrogen demand in the EU will likely be met by several different regions, and will necessitate international cooperation[45]



Strict regulations and lack of long-term deals stunt low-carbon hydrogen market

Cost, regulation, renewable energy supply, storage and transportation barriers hinder the creation of a successful international hydrogen market and impede regions and nations from meeting climate commitments.

Prohibitively expensive for offtakers

The price of clean hydrogen is significantly higher, in some cases a multiple, of the fossil equivalent. To compare pricing per MWh, the price of natural gas is currently €30-50, while low carbon hydrogen could be ~€100, and renewable hydrogen ~€200-250)[46]. This results in offtakers being unable to make binding agreements, thereby making it challenging for hydrogen producers to raise financing as they do not have any offtake agreements in place. These differences can be bridged with funding, with CFDs, or if off-takers are able to handle the increased cost of low-carbon hydrogen.

Producer investment strained

For producers, the difficulty is threefold:

a. Investment costs for production facilities are very high, and due to low realization rates, the scaling effect is lagging.
b. Because of excessive price of clean hydrogen, the inability to secure contracts results in inability to secure financing
c. Construction material inflation and growing interest rates are negating any growth in the scaling improvements being achieved.

Government & regulatory support

Europe's high sustainability standards for renewable electricity generation and hydrogen production, such as additionality and time/local correlation, create barriers to increasing production.

In Europe, the experience is that CAPEX funding is necessary but insufficient on its own. Support mechanisms must also address the significant OPEX cost gap between clean hydrogen and fossil alternatives. Governments and regulators may need to bridge this cost gap for the next decade or two, similar to the support provided in the early years of the wind and solar power markets, to allow the hydrogen market to grow and scale up.

Insufficient supply of renewable electricity

Renewable electricity is essential for producing renewable hydrogen. To generate 10Mt of renewable hydrogen, around 500TWh of electricity is needed, (~25,000 new wind turbines). This roughly equals Germany's 2022 net electricity consumption to produce the EU's requirement for 10Mt of renewable hydrogen[47]. Other sectors will also need more renewable energy as they electrify, increasing competition for this resource. For example, European road transport will require 130TWh by 2030 and 350TWh by 2040[48]. Hence, low-carbon hydrogen from natural gas may be needed to bridge this gap initially.

Infrastructure Challenges

The lowest-cost hydrogen production areas are often far from consumption centers, creating a significant barrier due to the lack of hydrogen infrastructure. Investment in, and developing and building a connected network requires substantial investment and coordination among stakeholders for the production, storage and distribution of hydrogen. The EU has recently made progress with initiatives like a core network in Germany, or an independent planning body for hydrogen. However, there is still a lack of international coordination (Strategy&, 2024).

Opportunities to improve the European hydrogen ecosystem

Overcoming the challenges described before requires joint industry efforts from all stakeholders and unified action and commitment from all ecosystem players[46].

Regulators and governments

Establish clear and supportive regulatory frameworks with defined targets and standards to provide a stable foundation for the necessary high levels of investment.

Foster international collaboration and harmonization of standards, regulations, and certification processes for hydrogen technologies to facilitate cross-border trade and investment, enabling global expansion of the hydrogen economy.

Streamline processes to expedite permitting and approval processes for clean hydrogen projects and the installation of renewable electricity production plants to reduce administrative burdens and delays.

Governments can also provide incentives to support research, development, and commercialization of hydrogen technologies. Governments, investors, and companies should increase funding through grants, subsidies, tax incentives, and low-interest loans to attract private investment and accelerate the growth of the hydrogen economy.

Producers

Hydrogen producers must prioritize cost competitiveness through technological advancements, economies of scale, and optimized production processes, supported by regulations and financial incentives. Forming consortia with offtakers will help secure volume buyers to build the required supply chains. By diversification of renewable electricity sources, establishing strategic storage facilities, and developing contingency plans, producers will be able to ensure reliable production.

Offtakers

Offtakers in hard-to-abate sectors need to commit to, and incorporate hydrogen into their energy mix with clear utilization timelines. Creating a stable demand encourages investment in infrastructure, achieving economies of scale and lowering costs. Collaboration between offtakers and producers can include long-term supply agreements, joint infrastructure development, and knowledge sharing with producers and distributors. Additionally, they can advocate for supportive policies and favorable market conditions liaising with regulators, industry associations, and policymakers. They can also invest in hydrogen-ready infrastructure, including fuel cell vehicles, storage facilities, and industrial processes utilising hydrogen.

Distributors, traders and intermediaries

To build out a successful global hydrogen market, the ecosystem is dependent on distributors and traders building the relevant infrastructure for distribution, as well as establishing protocols and and safety guidelines to develop a reliable and safe supply chain.

The role of aggregators is important for scaling up the hydrogen economy. Aggregators aggregate demand, ensuring viability of larger projects and converting long-term contracts favored by producers into short-term contracts required for offtakers. With assistance of government or private funding, they bridge price differences and market inefficiencies, optimizing procurement economics and creating an active and sustainable market (Strategy&, 2024).

Green solutions are more expensive than using conventional technologies, and successful implementation will require public subsidies or price premiums in the market

Using carbon capture or hydrogen will be more expensive than using unabated fossil fuels in the short term, and it is estimated that the energy transition will require between €400 to €575 billion per year in investments[49]. In order to attract investments in the value chains for CCS and hydrogen, the companies that implement these technologies in their production facilities will require price premiums for their products, or they will need public support until the market conditions are favorable enough. Today, we observe positive trends both for public willingness to support such projects, and in market willingness to pay for green products.

Currently, the EU has several support schemes for investments that lead to environmental benefits. Through various mechanisms, the EU has committed to supporting the transition to cleaner technologies with over €800 billion by 2027 through R&D support, loans and direct grants and funds[50]. This support is expected to lead to significantly more private investments in the EU.

Furthermore, early adopters of clean technologies, including implementing a first of a kind carbon capture system in cement production, and green hydrogen in fertilizer production, have demonstrated that there may be a market for green products. The Table on the right illustrates three Norwegian examples that highlight early positive experiences in the market for greener commodities.

Company	Project	Quote/Experience/Customer
Yara[51]	Green hydrogen production on Herøya. Used for ammonia production in fertilizer production.	"The first tonnes with green fertilizer are already delivered to Lantmännen. The company is collectively owned by Swedish farmers, and sells mainly grain under the Axa brand and baked goods under the Hatting brand."
Heidelberg Cement[52]	CCS on cement plant in Brevik, first of a kind in Northern Lights.	"Together with the Nobel Center project, we aim to set a new standard for sustainable construction and pave the way for other future-oriented players. The collaboration enables us to combine the world of science and innovative solutions from our own sector such as evoZero in an exciting way."
Hydro[53]	Hydro CIRCAL – premium recycled aluminium with significantly reduced emissions.	"Recycling is the fastest way to zero emissions, and Hydro CIRCAL has a market-leading CO_2 footprint," she explained. "It is sold out in Europe. This is why we are investing here and at our other recyclers." - Hilde Merete Aasheim

Summary

The North Sea has a tremendous potential to contribute to the energy transition in Europe. Through offshore wind, the North Sea can supply large amounts of renewable electricity to the European power system, and the large storage capacities for CO_2 allow the North Sea to enable emissions reduction in sectors that cannot be electrified. Renewable power from offshore wind can also power electrolyzers to produce green hydrogen, and natural gas from the North Sea also synergizes well with CCS through blue hydrogen production, potentially supplying large volumes of low cost hydrogen to the European market.

The actual evolution of the North Sea depends on several factors, including developments of regulatory frameworks and technological innovations. The analysis in this report has assumed a technology neutral outlook, and a highly cooperative environment between the European countries, where the countries share the goal of collectively supplying enough energy to meet all needs for the lowest cost. These assumptions, together with our assumptions on technological development in the energy sector, are important considerations when applying our results. Our findings for the power sector are in line with other studies on the same topic, primarily showing a large growth in renewable power generation. However, our results on the share of blue and green hydrogen production, as well as our results showing a prolonged use of coal in the power system, can be attributed to differing assumptions on policy, energy availability and technological developments.

Regardless of these assumptions, it is clear that the European energy transition will require large investments into energy production, transmission, conversion and storage. The EU has committed to subsidizing these investments through several large sources, but the transition will also require considerable engagement from private investors as well. Fortunately, early adopters have demonstrated positive experiences with green production, with significant market interest into green products, leading to favorable price premiums. Continuing on this path in the North Sea will ensure maintained European industrial development in energy-intensive industries, and alignment with the climate goals set by the EU.

References

1 European Commission, 2019. "The European Green Deal"
2 European Commission Press Release, 2019. "The European Green Deal sets out how to make Europe the first climate-neutral continent by 2050, boosting the economy, improving people's health and quality of life, caring for nature, and leaving no one behind"
3 European Commission, 2018. "A Clean Planet for all; A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy"
4 European Commission, 2008. "Proposal for a directive of the European parliament and of the council amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading system of the Community"
5 European Commission, 2024. "The Monitoring and Reporting Regulation – General guidance for ETS2 regulated entities"
6 European Commission, 2022. "REPowerEU Plan"
7 European Commission, 2023. "Proposal for a regulation of the European parliament and of the council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act)"
8 Eurostat, 2024. "Greenhouse gas emissions by source sector." https://ec.europa.eu/eurostat/databrowser/view/env_air_gge__custom_11620902/default/table?lang=en
9 Eurostat, 2024. "Complete energy balances." https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_c__custom_11621065/default/table?lang=en&page=time:2022
10 European Commission, 2020. "Powering a climate-neutral economy: An EU Strategy for Energy System Integration"
11 IRENA, 2024. "Decarbonising hard-to-abate sectors with renewables: Perspectives for the G7"
12 Harvard, 2022. "Clean Hydrogen: A long-awaited solution for hard-to-abate sectors." https://seas.harvard.edu/news/2022/10/clean-hydrogen-long-awaited-solution-hard-abate-sectors
13 DNV, 2023. "Energy transition outlook 2023"
14 European Commission, 2023. "Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652"
15 European Commission, 2020. "An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future"
16 European Commission, 2023. "Member States agree new ambition for expanding offshore renewable energy." https://energy.ec.europa.eu/news/member-states-agree-new-ambition-expanding-offshore-renewable-energy-2023-01-19_en
17 Durakovic Goran, Hongyu Zhang, Knudsen Brage Rugstad, Tomasgard Asgeir & Crespo del Granado Pedro, 2024. "Decarbonizing the European energy system in the absence of Russian gas: Hydrogen uptake and carbon capture developments in the power, heat and industry sectors"
18 Eurostat, 2024. "Share of energy from renewable sources." https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_ren__custom_11688285/default/table?lang=en
19 Equinor, 2024. Energy Perspectives: Global macroeconomic and energy market outlook"
20 European Commission, 2024. "EU coal regions in transition." https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/eu-coal-regions-transition_en
21 Eurostat, 2024. "Supply, transformation and consumption of gas - monthly data." https://ec.europa.eu/eurostat/databrowser/view/nrg_cb_gasm__custom_11679397/default/table
22 Eurostat, 2024. "Supply, transformation and consumption of gas." https://ec.europa.eu/eurostat/databrowser/view/nrg_cb_gas__custom_11678474/default/table?lang=en
23 IEA, 2023. "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach – 2023 Update"
24 Durakovic Goran, Crespo del Granado Pedro & Tomasgard Asgeir, 2023. "Powering Europe with North Sea offshore wind: The impact of hydrogen investments on grid infrastructure and power prices"
25 Wind Europe, 2019. "Our energy, our future; How offshore wind will help Europe go carbon-neutral"
26 North Sea Wind Power Hub, 2022. "Hubs and spokes – viable beyond theory. Sharing of Feasibility Results"
27 Danish Energy Agency, 2024. "Denmark's Energy Islands." https://ens.dk/en/our-responsibilities/offshore-wind-power/denmarks-energy-islands
28 Intergovernmental Panel on Climate Change, 2022. "Climate Change 2022; Mitigation of Climate Change"
29 European Commission, 2024. "Towards an ambitious Industrial Carbon Management for the EU"
30 IEA, 2022. "CCUS Policies and Business Models; Building a commercial market"
31 IEA, 2022. "Coal 2022"
32 Ember Climate, 2024. "European Electricity Review 2024"
33 Global CCS Institute. "CCS in Europe; Regional overview"
34 IEA, 2024. "CCUS Projects Database." https://www.iea.org/data-and-statistics/data-product/ccus-projects-database
35 SINTEF blog, 2023. "The finalisation of a clear incentive for CCUS in Europe just arrived – why did it take so long and what can emerging emissions trading systems learn?" https://blog.sintef.com/sintefenergy/ccs/a-clear-regulatory-incentive-for-ccus-in-europe-just-arrived-why-did-it-take-so-long-and-what-can-emerging-emissions-trading-systems-learn/
36 IEA, 2023. "Global Hydrogen Review 2023"
37 European Commission, 2024. "Supporting clean hydrogen." https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen_en
38 Aurora Energy Research, 2021. "Enabling the European hydrogen economy"
39 Hydrogen4EU, 2022. "Hydrogen4EU – Charting pathways to enable net zero"
40 European Commission, 2023. "METIS 3- Study S5. The impact of industry transition on a CO_2-neutral European energy system"
41 Durakovic Goran, Crespo del Granado Pedro & Tomasgard Asgeir, 2023. "Are green and blue hydrogen competitive or complementary? Insights from a decarbonized European power system analysis"
42 World Energy Council, 2022. "Regional insights into low-carbon hydrogen scale up"
43 Federal Ministry for Economic Affairs and Climate Action (BMWK), 2023. "National Hydrogen Strategy Update"
44 IEA, 2023. "Hydrogen Projects Database." https://www.iea.org/reports/hydrogen-projects-database
45 European Hydrogen Backbone. 2022. "Five hydrogen supply corridors for Europe in 2030"
46 Strategy&, 2024. "Navigating the hydrogen ecosystem; What is preventing progress and how to gain momentum?"

47 Statista, 2024. “Nettostromverbrauch in Deutschland in den Jahren 1991 bis 2023.” https://de.statista.com/statistik/daten/studie/164149/umfrage/netto-stromverbrauch-in-deutschland-seit-1999/
48 PwC, 2023. “European Fleet Electrification. From Electric Vehicle Sales to a complete Fleet Transition”
49 European Investment Bank, 2023. “EIB Energy Lending Policy; Supporting the Energy Transformation”
50 European Parliamentary Research Service, 2023. “Energy transition in the EU”
51 E24, 2024. “Yara åpnet nytt anlegg: – Banebrytende.” https://e24.no/energi-og-klima/i/LM1WwR/yara-aapnet-nytt-anlegg-banebrytende
52 Heidelberg Cement, 2024. “New Nobel Center opts for net-zero concrete from Heidelberg Materials.” https://www.heidelbergmaterials.com/en/pr-2024-02-14
53 Light Metal Age, 2024. “Hydro Celebrates the Opening of Its New Recycling Plant in Cassopolis.” https://www.lightmetalage.com/news/industry-news/recycling-remelt/hydro-celebrates-the-opening-of-its-new-recycling-plant-in-cassopolis/