Nordic Energy Research

Hydrogen, electrofuels, CCU and CCS in a Nordic context

2022

CONTENTS

Foreword

The Nordic countries aim to maintain a leading role in the energy and climate transition towards a low-carbon society. The Nordic region is well positioned for this, but we need to act fast to hit the unique window of opportunity for the Nordics to take the lead.

All Nordic countries are in the process of developing national hydrogen strategies and road maps. These road maps will complement the European Hydrogen Strategy and the New Green Deal as well as the tremendous global interest in hydrogen and its applications – including CCS and CCU – and how it can contribute to the green transition. With the Nordic Prime Ministers Declaration on Nordic Carbon Neutrality in 2019, and with the common vision of the Nordic region to become the most integrated and sustainable region in the world, it is obvious also to look for Nordic solutions.

The unique position held by the Nordic countries is illustrated by the numerous activities taking place and the vast industrial interest in these emerging technologies. Currently, the Nordics are ramping up production and distribution of renewable hydrogen and ammonia, including various types of electrofuels. In addition, the Nordics are in the works of establishing distribution infrastructure and deploying carbon capture and storage technologies.

There are promising synergies between the efforts in the Nordic countries. For example, some have cutting edge electrolysis companies, some excel in production of fuel cells and others have extensive experience in capturing and storing CO_2. The Nordic governments are working closely with private actors to boost the introduction of low-carbon solutions and have also supported many innovative pilot and demonstration projects in recent years.

The Nordic region is jointly in an excellent position to deploy innovative solutions due to ambitious energy and climate policy goals, as well as extensive research programs. The Nordic region already hold a pole position in the green transition and this report has mapped the challenges, conditions, and opportunities, that the Nordic countries can apply to further upscale innovative technologies in the coming years. I hope that you will find this report useful and inspiring. I believe that you will gain new insights on the rapidly evolving landscape of hydrogen, electrofuels, CCU and CCS in a Nordic context and use those insights as a foundation for further research and policy formation.

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Executive summary

The Nordic countries aim to maintain a leading role in the energy and climate transition towards a low-carbon society. All Nordic countries are in the process of developing or implementing their own national hydrogen strategies and road maps, while also exploring renewable hydrogen, electrofuels and associated carbon capture technology solutions. The international focus on hydrogen and its applications – as well as CCS and CCU – is growing steadily. Building on the identification of Nordic strengths and synergies in this report, the following recommendations and remarks can sum up the findings.

Recommendations

National level

> **Study the potential for hydrogen storage**. The countries could study the potential for hydrogen storage in salt caverns as well as how to utilise these as part of the future energy system, for instance in relation to the Baltic pipe network.

> **Investigate the energy and climate effects of CCUS technology**. To further harvest potential synergies from the ongoing development of CCUS in each country, the countries could investigate how different elements of the CCUS chain in each country and transnationally affect the joint Nordic energy system and binding climate commitments.

> **Work for the ratification of the amendment of Art. 6 in the London Protocol**. The Nordic countries are recommended to increase the ratification level of the London Protocol, which provides a legal basis for the transport of CO_2 across national borders. Although bilateral agreements between countries are now a viable option, ratification of the protocol is of considerable symbolic value.

> **Investigate planned power production**. Harvest potential synergies from renewable power in each country and investigate if any changes could be made to policies or power-transmission practices to improve the conditions of renewable hydrogen, electrofuels and CCUS.

Nordic level

- > **Continue the stakeholder involvement**. The countries should continue their focus on Nordic stakeholder involvement to address financial, technical and regulatory challenges.

- > **Collaborate on the potential for biomass**. Map the national as well as the collected Nordic potential for biomass, and consider strategies for the future deployment of biomass, including CO_2 storage opportunities.

- > **Develop cross-Nordic training programmes**. Increase the skills needed hydrogen and electrofuel production and CCUS.

- > **Develop a plan for the Nordic power mix.** The Nordic countries could develop a plan for ensuring sufficient access to a renewable Nordic power mix, to harvest synergies from the availability of different types of renewable power in each country.

- > **Establish ambitious goalsetting by the leading offtakers**. Implement a scheme that ensures financial incentives for the production and offtake of renewable hydrogen, electrofuels and CCUS technologies, such as CO_2 pricing, taxation, or reversed auctioning.

- > **Develop a Nordic model for hydrogen distribution**. Identify solutions to Nordic cross-border infrastructure for hydrogen distribution, that have direct access to major international markets.

- > **Develop a Nordic network for carbon storage facilities**.

- > **Collaborate on regulatory measures**. Develop regulatory measures that encourage the development of a coherent Nordic hydrogen transmission net, for the distribution of large-scale renewable hydrogen to energy production facilities or various offtake sectors in the Nordics, or as export to the EU.

International level

- > **Closer collaboration within the international institutions**. Seek consensus within EU and UN on how to assess biogenic carbon as part of international carbon schemes, including financial support mechanisms.

- > **Closer collaboration in international processes**. Actively work within the UN and EU to assess usage of carbon from hard-to-decarbonize sectors.

Technological pathways

Increased production of and capacity for **renewable hydrogen by electrolysis** is already planned in all countries. The technology is mature but commercially not competitive. The capital investment of the electrolysers contributes significantly to the cost, and the high CAPEX for the electrolyses needs to be reduced through mass production or new and improved technologies to bring down the price. Thus, further research and development is needed on how to bring costs down.

Norway, Sweden, and Finland all lack a national natural gas network that can be converted into a hydrogen network. Hydrogen will mainly be for use in heavy industries and is likely to be produced next to the consumer. In Denmark, renewable hydrogen will either be used to produce e-fuels or be exported through the coming European backbone hydrogen network. In Iceland, the renewable hydrogen could be converted into e-fuels for export.

The use of **renewable ammonia** is expected to increase for both fertiliser and marine e-fuels. The advantage of renewable ammonia is that its production does not require a CO_2 source, it is easy to transport and it is an established commodity. Thus, ammonia can be produced at remote locations with access to cheap renewable electricity. Ammonia is not yet approved or tested in marine engines, but there are ongoing projects to test the feasibility.

Electrofuels are expected to impact aviation and shipping in all countries, most likely as sustainable jet-fuel for aviation and either ammonia or methanol for marine. For short distance ferries, batteries or hydrogen will be an option. The technology for producing **e-biofuels** requires further development before reaching technical and commercial maturity. The Nordic region has an advantage due to large bio resources primarily from the large forest and pulp and paper industry, and in Denmark from the agricultural sector. Iceland's bio resources are by comparison small.

Norway and Denmark are looking into using part of the existing oil and gas infrastructure in the North Sea for **carbon capture and storage facilities**, while Iceland is working on processes for binding the CO_2 in minerals.

Cost implications of the different technologies are still difficult to predict due to rapid development. Lower renewable electricity prices and the interconnecting infrastructure, improved efficiency in the electrolysis plants and improved regulatory framework for sector coupling is likely to affect the overall prices the overall cost. The electricity price makes up about half of the cost of producing hydrogen.

International trends and development

In the EU, the **Hydrogen Strategy** is a key policy initiative which aims at decarbonising hydrogen production and expanding its use in sectors where it can replace fossil fuels. It sets the objective of installing at least 6 GW of renewable hydrogen electrolysers by 2024 and at least 40 GW of renewable hydrogen electrolysers by 2030.

In addition, several **Member States** intend to convert the existing methane infrastructure for hydrogen distribution and to set up a market for hydrogen. Industry, mainly in the oil refining, steel, ammonia, fertilisers, and pharmaceutical sectors is seen as a target sector by many countries. Finally, there seems to be increasing support in developing an international transportation infrastructure, such as a European Hydrogen Backbone.

Outside of Europe, the hydrogen supply is expected to come from locations with strong solar and wind resources. There is a strong international momentum in using renewable hydrogen, electrofuels and CCUS technologies for tackling the challenges and reaching GHG reduction targets. In addition, there is a rapid increase in private sector initiatives that focus on improving technologies and establishing full value-chain collaboration.

The economic **business case** for each of the technologies is improving due to significant cost reductions. However, large investors still appear reluctant and there is a need for clarity on viable business models that de-risk investments. One option is to subsidise producers, and another option is to develop regulatory returns models. Subsidies can give certainty to producers, while regulatory models may be easier to implement, given the existing institutional capabilities. Incentivising the use of renewable hydrogen with end-user subsidies or blend-in obligations is more challenging as this leaves significant policy-related risks with the producers.

Benefits and risks

Energy-intensive industries offer the biggest opportunity for GHG reductions. In transport, most Nordic countries see a potential to use hydrogen as fuel in **heavy transport and short-distance shipping**. One precondition for this is a hydrogen supply infrastructure along the main road network and in major ports. There is a large potential for climate benefits using electrofuels for coastal and medium range shipping. For the Nordic countries with high volumes of domestic aviation **introducing sustainable aviation fuels and electric aviation** could contribute to achieving the national reduction targets. For both freight and light duty vehicles, there is a potential for the use of electrofuels as drop-in fuels in a transition phase.

The use of electrofuels within **agriculture** could be a viable option for agriculture dense areas in Denmark and southern Sweden. Specifically, ammonia is already used for land fertilisation, which could easily be replaced by renewable ammonia.

Regarding CCS, the present study concludes that the technology is only advisable for non-biogenic material in sectors where decarbonisation is otherwise difficult. This includes, for instance, cement production in Denmark, Sweden and Norway, for which there are currently few decarbonisation options. Within these areas, the technology appears to have large potential.

The present study also identifies measures to mitigate the negative **environmental impacts** of the adoption of the hydrogen, electrofuels and CCUS technologies. An efficient use of each energy source to ensure the maximum displacement of fossil fuels is important. Attention must be given to the location of production plants, to avoid local water scarcity and to ensure closeness to district heating plants to utilize surplus heat. More knowledge must be generated on the risks, level and impact of possible hydrogen leakage and nitrous oxides to the atmosphere. There is a need to improve the effectiveness of methods to assess safety and health risks from producing, storing, and utilizing renewable hydrogen. The origin of the CO_2 for CCUS must be considered as well as safety and health risks in capturing, transporting, utilising or storing CO_2.

Nordic strengths and synergies

Each of the Nordic countries has **ambitious energy and climate policy goals** and they are currently working towards developing or implementing their individual national strategies for hydrogen, electrofuels and CCUS as supplements to their climate strategies. Further, the Nordic countries have **invested considerably in research and development** within these fields, supporting the already strong research environment on related subjects in the Nordic universities and the strong partnerships across the private sector and universities.

Going to market, the Nordic countries has given **considerable support to pilot projects and companies** seeking to engage in the markets for clean energy and CCS and are currently looking at additional financial incentives for the offtake sectors, such as an increased CO_2 tax.

The Nordics have a high availability of **affordable natural resources and renewable energy** for the production of renewable hydrogen and storage of carbon. They have steel and iron industries that can be decarbonised through new uses of low-carbon hydrogen natural gas processing points.

On **carbon storage**, the Nordic countries already benefit from cross-Nordic collaboration, in a project where Finnish and Swedish companies will ship captured CO_2 to storage points off the west coast of Norway. In addition, Denmark is looking into its North Sea storage potential.

Finally, the Nordic countries also enjoy comparative strength in the development of **appropriate infrastructure and distribution systems.** For example, by developing a Nordic port infrastructure for hydrogen distribution that has direct access to major international markets via ocean freight.

Chapter 1

INTRODUCTION

In June 2020, the European Commission (2020) presented its hydrogen strategy "A hydrogen strategy for a climate-neutral Europe". This strategy is a road map describing renewable hydrogen as an important part of the European Green Deal and of the necessary energy and climate transition within the EU. The Commission has announced that 430 billion euros will be allocated to renewable hydrogen development in Europe. In addition, a broad coalition called the European Clean Hydrogen Alliance has been formed to identify archetypes and prototypes for the production, transport and use of hydrogen within Europe, including the integration of carbon capture and usage (CCU) as well as carbon capture and storage (CCS).

The Nordic countries aim at maintaining a leading role in the transition towards a low-carbon society. Therefore, in the light of the European strategy and the need for identifying solutions for reducing greenhouse gas emissions in transportation and industry, the Nordic countries are developing their own national hydrogen strategies and road maps. The international focus on renewable hydrogen and its applications – as well as CCS and CCU – regarding their contributing to the goals of achieving a carbon neutral society is growing steadily. This is illustrated by the many activities taking place and the industrial interest in these technologies.

The preconditions for introducing the new technologies in the regions are of technical, market, systemic and regulatory character and include, for instance, the availability and allocation of resources, development of energy system models to include renewable and low-carbon hydrogen and electrofuels, co-optimising the energy grid infrastructures, regulation of vehicles, plants and safety and environmental concerns. These preconditions vary across the Nordic countries, as the countries vary both in terms of their geographical and political starting points for the production of the technologies as well their expected offtake sectors.

This report aims at identifying these preconditions and supporting the Nordic countries in maintaining this leading role in the energy and climate transition by accumulating knowledge and identifying the role of renewable hydrogen, electrofuels and carbon capture technologies in the future low-carbon Nordic energy supply. It intends to accumulate knowledge and identify the role of renewable hydrogen, electrofuels, CCU and CCS in the future Nordic energy supply. Furthermore, the report assesses the current strengths and potential synergies for the Nordic countries and identifies what is needed for achieving the synergies across the countries.

The definition of "clean hydrogen" used in the report covers both low-carbon hydrogen and renewable hydrogen. Low-carbon hydrogen is fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared with the existing hydrogen production. Renewable hydrogen is hydrogen produced by the electrolysis of water (in an electrolyser, powered by electricity) and with electricity from renewable sources.[1]

The content of the study is an overview of the present situation and future needs for hydrogen, electrofuels, CCS and CCU in the Nordic countries and an assessment of strengths and potential synergies in

1 Renewable hydrogen may also be produced by reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with the sustainability requirements.

the Nordic region. For this, an introduction to the technologies and the international trends and development that influence the Nordic actors is included.

The study is, apart from the executive summary and introduction, divided into six main chapters (chapters 2–6), and the concluding remarks and recommendations are in chapter 7.

Chapter 2, **Technology pathways**, provides an overview of the solutions that will allow renewable power to be converted into sustainable electrofuels, through the use of renewable hydrogen, CCU and bio-CCU. The potential for storing CO_2 is also addressed.

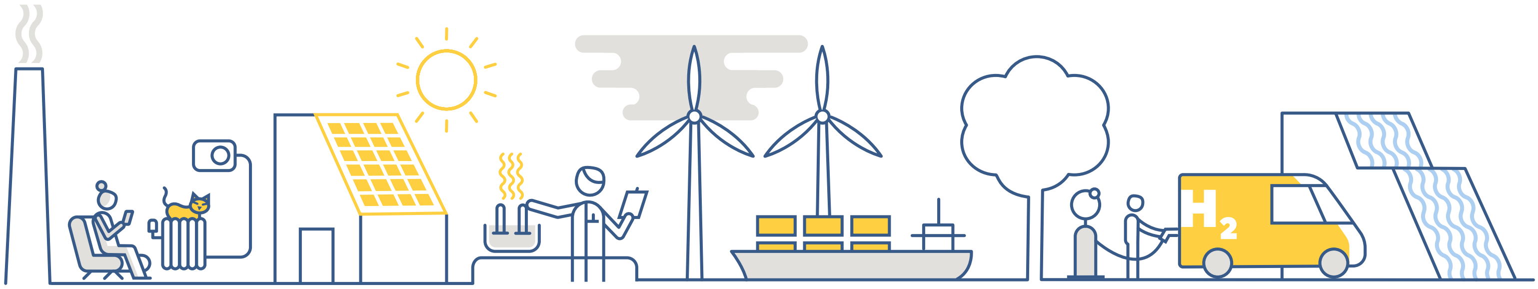
Chapter 3 describes the **international development** through international agreements, collaborative opportunities and market framework for the Nordic countries on the various technologies. The content focuses on EU initiatives, trends and market development. The chapter is concluded by a discussion of the possibilities for developing viable business models for the technologies.

Chapter 4 provides an overview of the **energy and climate benefits** for the Nordics from developing the technologies from an energy and climate transition perspective.

Chapter 5, on **Nordic policies and measures**, introduces the political goals, existing support measures and policies within the fields of energy, climate and business that directly affect the development of hydrogen, electrofuels, bio-CCUS and CCUS.

Chapter 6 identifies the **Nordic strengths and potential synergies**. The chapter shows the strengths of the Nordic region in the rapidly evolving international development within PtX and CCS/CCU and discusses the potential Nordic synergies taking into account the demands, needs and opportunities as well as covering PtX and CCUS.

Chapter 7 contains the **concluding remarks and the way forward**, including recommendations for pursuing the objectives for the Nordic countries.



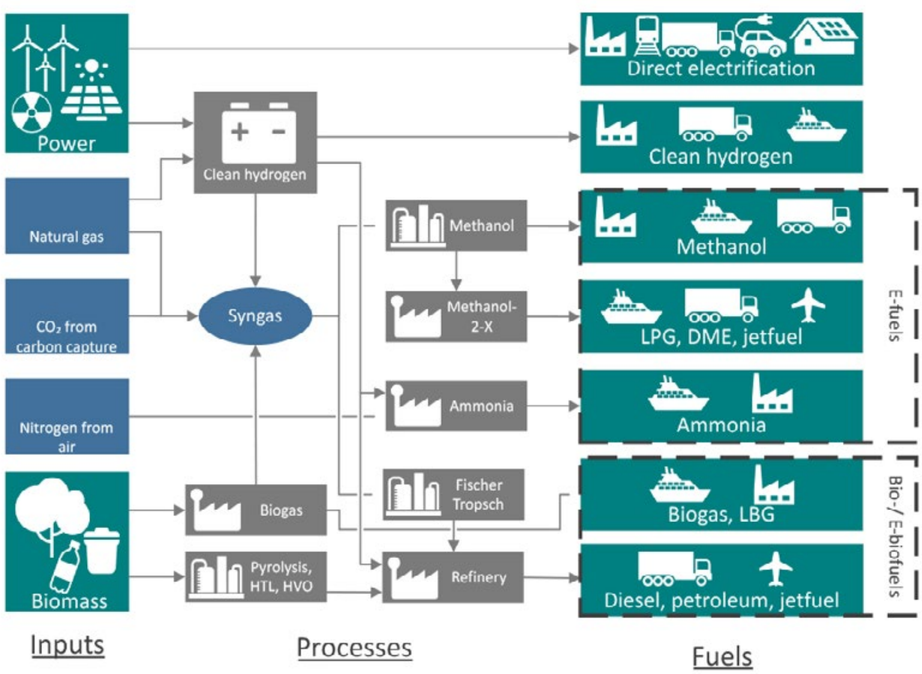
Chapter 2

TECHNOLOGY PATHWAYS

This chapter provides an overview of the technical status of the various technology pathways that will allow renewable power to be converted into sustainable electrofuels through the use of clean hydrogen, CCU and bio-CCU. The potential for storing CO_2 is also addressed (CCS). First, the technologies as well as their applications (end-user) and maturity level are described in a general manner, common for all countries. Afterwards, there is a description of the relevance of using various technologies and fuels in the individual countries.

The terms renewable hydrogen, low-carbon hydrogen, e-fuels and e-biofuels cover a wide range of technologies which can all play a role in the future 100% renewable energy system. Figure 2.1 provides an overview of the different technology pathways to produce clean fuels. From the figure, power can be utilised in three different categories: Direct electrification, clean hydrogen and liquid fuels (both e-fuels, biofuels and e-biofuels). Whenever energy is converted from one carrier to another, energy is lost. For that reason, the most efficient use of the power is direct electrification, which should be used whenever possible. This includes electric batteries in light transport, railway, heat pumps in households where district heating is not available and more use of electricity in industry.

Figure 2.1 Technology pathways for the production of clean fuels.



In the heavy transport sector, the use of electric batteries is more difficult, and may only be practicable for short distances without recharging. Thus, when looking towards 2050, alternative fuels will become a much more significant part of the energy mix and renewable power in the transport sector will depend, amongst others, on the technical and economic viability. For instance, renewable power can be converted by electrolysis to renewable hydrogen which may be used in heavy land transport or smaller ships. This is illustrated in Figure 2.1 as the pathway from power to clean hydrogen via electrolysis. Hydrogen can be used in fuel cells to power electric motors; this allows more energy to be stored on board the vehicle or vessel than if electric batteries are used. This allows heavier transport and longer travel distances, at the cost of an additional energy loss in the electrolysis process. Clean hydrogen can also be utilised in industry to replace fossil-based hydrogen.

Another option is the production of liquid fuels. They resemble fossil fuels but have the lowest overall energy efficiency from power to end-user fuel. A combination of hydrogen, biomass and process gases (CO_2 or nitrogen) can produce several liquid fuels which may be used in already existing combustion engines and industrial processes. In Figure 2.1, clean hydrogen is used as an input in combination with biomass, nitrogen or CO_2 to produce a variety of fuels. The left-hand side of the figure shows the inputs, the grey boxes are the processes and the green boxes, on the right-hand side of the figure, are the finished fuel products and the sectors where they can be used.

In the following sections, the technologies of clean hydrogen, e-fuels, biofuels and carbon capture is introduced in four separate sections. They provide a status of the technology development and prerequisites of resources in each of the Nordic countries. The chapter is concluded with an overview of the five countries' availability of the required renewable power and other factors.

2.1 Clean hydrogen

Clean hydrogen can be produced by the electrolysis of water with the three available technologies being alkaline electrolyser, poly exchange membrane (PEM) electrolyser and solid oxide electrolyser. The electrolysis process is technologically mature at TRL 8-9 and, therefore, the biggest challenge is the production price of renewable hydrogen which is still significantly higher than low-carbon and fossil-based hydrogen produced from natural gas. Currently, the price of renewable hydrogen is more than twice that of hydrogen produced from natural gas, mainly due to the renewable electricity price (Recharge news, 2021). In the production of liquid fuels, the cost of hydrogen constitutes a significant share of the total production cost, depending on the conversion technologies. Therefore, lowering the production cost of renewable hydrogen is also important for promoting the production of liquid fuels.

An alternative is low-carbon hydrogen produced from natural gas (steam gas reforming). This is a well-known process and how more than 90 per cent of the hydrogen is produced today. What could make it 'low-carbon' is that the CO_2 could be captured and stored.

There are two main paths for the use of clean hydrogen:

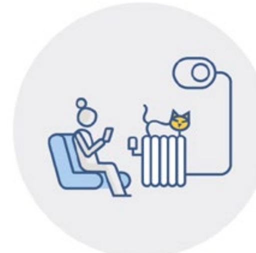
- **Direct utilisation**: The clean hydrogen is compressed, transported and stored. It can then be utilised as a direct fuel instead of natural gas in industry or in fuel cells to produce electricity for electric motors in both the transport sector and industry.

- **Utilised as a feedstock for e-fuels and e-biofuel**: The clean hydrogen is compressed and transported to specific sites where it is utilised as a feedstock for the production of a wide range of renewable liquid fuels. This is described further in the next sections.

As clean hydrogen is the main source in all technology pathways, the price of clean hydrogen is the most important to address. The cost for establishing the value chain of hydrogen production depends on the technology pathway. However, even within the same pathways, the expected cost varies greatly. The cost of renewable power is the single most important source of producing competitive renewable hydrogen, as the power makes up about half of the production price. After that, the capital investment of the electrolysers also significantly contributes to the cost of renewable hydrogen. The high capital expenditure (CAPEX) for the electrolyser needs to be reduced through mass production or new and improved technologies to bring down the price.

According to the Hydrogen Council (2021), some of the key drivers for continued cost reduction in electrolysis include the industrialisation and improvements of electrolyser manufacturing and the use of low-cost renewable power.

Most of the sectors expect a drop in the production costs, especially led by reduced electricity prices and infrastructure, improved efficiency in the electrolysis plants and improved regulatory framework for sector coupling. According to the Hydrogen Council (2021), some of the key drivers for continued cost reduction in electrolysis include the industrialisation and improvements of electrolyser manufacturing and the use of low-cost renewable power. Although the experience in electrolysis is limited, it seems electrolysers have a similar relationship between cost decrease and capacity as solar PV – which potentially could lead 40 per cent cost reduction (IRENA, 2020).



The remaining part of the section is a description of each of the Northern countries' current use of clean hydrogen, ongoing and upcoming projects as well as their vision going forward.

Norway has extensive industrial experience with the hydrogen value chain, both fossil-based (hydrocarbons) and with electrolysers, the Norwegian/Danish company NEL being one of the leading providers of electrolyser technology. Almost all hydrogen utilised in Norway is used as an input in the chemical industry and for the refining of petroleum products. The production of hydrogen in Norway, as well as globally, is almost exclusively produced by reforming natural gas currently without the capture and storage of CO_2 (CCS), which causes large emissions.

Heavy road transport is likely to rely on renewable or low-carbon hydrogen in the future, but this will require extensive development of hydrogen fuelling stations both along major roads and in ports.

Renewable or low-carbon hydrogen can be a replacement of fossil-based hydrogen in the chemical and refining industry. It can be mentioned that the pig iron and titanium dioxide clinker plant Tizir in Tyssedal works to develop and test the technology needed to use hydrogen as a reducing agent in titanium oxide production.

Norway does not have an domestic natural gas pipeline network that can be refurbished to hydrogen, and most likely the clean hydrogen will be produced close to the end-users in Norway. However, there is an extensive gas-pipeline network to Europe that could be retrofitted to clean hydrogen and give Norway a major export opportunity. In the maritime industry in Norway, the funds from Enova awarded Wilhelmsen's Topeka Hydrogen Project NOK 219 million that plans to construct the world's first zero emission hydrogen vessels. The vessels will move goods and transport hydrogen to different filling stations for local ferries and land transport to use as fuel.

The current use of hydrogen in **Finland** is concentrated in the oil refining and biofuels sector (88%) and the main production method is fossil-based steam gas reforming. Finland already has considerable experience with the industrial use of hydrogen, particularly in oil refining and biofuel

production. Finland produces two million kg of fossil-based hydrogen for transport and communications every year.

The Finnish chemical industry company Woikoski owns the largest hydrogen electrolysis facility in Europe. The company aims at opening 20 filling stations all over Finland by 2030. The potential for clean hydrogen sale in Finland is estimated at 100,000-150,000 tonnes (approximately 3-5 TWh of hydrogen) by 2030, without considering any additional use in industry or the transport sector. The growing pressure to reduce emissions in other sectors, such as ore refining, and the high hydrogen demand in the steel industry are expected to expand the need for clean hydrogen further.

Sweden has the largest heavy industry sector among the Nordic countries and has a substantial usage of hydrogen. The chemical and refinery industry accounts for about 99% of the hydrogen produced and used in Sweden today, while direct use of hydrogen, as vehicle fuel or in the metallurgical industry, account for the remaining one per cent. Production and use in Sweden are around 180,000 tonnes of hydrogen per year (equivalent to about 6 TWh/year hydrogen) and it is mainly of fossil origin (67 per cent), the second largest source is industrial residual streams (30 per cent), while just under three per cent is produced via electrolysis.

There are currently several major plans and ongoing industrial projects in Sweden, where the production and/or use of hydrogen is central to one or more new value chains at the same time:

- HYBRIT, the most well-known hydrogen investment in Sweden (Hydrogen Breakthrough Ironmaking Technology), is a joint venture of SSAB, LKAB and Vattenfall. HYBRIT aims at developing a fossil-free steel value chain. Fossil coke used to reduce (remove oxygen from) the iron ore is replaced with a process based on direct reduction with fossil-free hydrogen from electrolysis for the production of iron sponge adapted for the production of crude steel in arc furnaces. The HYBRIT technology has the potential to reduce Sweden's total carbon dioxide emissions by at least ten per cent. LKAB will also use the hydrogen-based technology developed within HYBRIT to completely phase out its production of iron ore pellets to produce fossil-free sponge iron, perhaps one of Sweden's largest industrial conversion projects of all time. The expected future level of production has not yet been published.

- Ovako AB; European manufacturer of engineering steel, is preparing the next demonstration step for steel heating using fossil-free hydrogen from electrolysis instead of natural gas or gasoil. This change has the potential to reduce Ovako's carbon footprint by 100,000 tonnes per year, corresponding to 50 per cent of the carbon dioxide emissions from its operations.

- Nouryon, a chemical industry has plans to replace fossil hydrogen gas with fossil-free hydrogen from electrolysis for its hydrogen peroxide production in Bohus and Ånge, and Borealis, in collaboration with Vattenfall, is investigating the possibilities of using hydrogen from electrolysis as cracker fuel to replace the fossil gas used today.

- H2 Green Steel is planning to produce steel using only renewable hydrogen to lower the high CO_2 emission of the fossil-based hydrogen which are used today (H2 green steel, 2021).

Generally, all hydrogen produced in Sweden is used near its production site. The distribution of hydrogen takes place exclusively on the road in compressed form. The expansion of hydrogen infrastructure in Sweden can be accelerated by establishing cross-sectoral local and regional hydrogen clusters of industries. They can be established where existing industries use or will use hydrogen and where infrastructure such as port and rail already exist.

Everfuel Sweden AB, a fully owned subsidiary of Everfuel A/S and OKQ8 have entered into a cooperation agreement for the joint development of the green hydrogen market in Sweden by establishing a network of H2 stations for zero-emission mobility in connection with existing and new OKQ8 service stations (Everfuel, 2021).

It is not considered realistic to establish a nationwide hydrogen network since Sweden lacks natural gas networks that can be converted to pure hydrogen. However, there is an extensive network between Sweden and Denmark that can promote cooperation between the countries by retrofitting the connection to transport pure hydrogen.

In the transport sector, both Scania and Volvo AB are investing in the development of hydrogen-powered trucks as well as using carbon-free steel for their chassis.

There is also a feasibility study ongoing to convert diesel locomotives to hydrogen operation on Inlandsbanan between Mora and Gällivare. For comparison, the first fuel-cell powered locomotives have been in operation in Germany since 2018 (Alstom).

In **Denmark**, the current production of renewable hydrogen is insignificant, but multiple large-scale projects are in the pipeline, all based on an expectation that massive amounts of cheap renewable power will be available. Planned and ongoing projects:

- Green fuels for Denmark – A joint project by Ørsted, Copenhagen Airports, DSV, DFDS, SAS and A.P. Møller-Mærsk aiming at producing 1.3 GW of green hydrogen in Copenhagen by 2030.

- Ammonia production in Esbjerg – A project by Copenhagen Infrastructure Partners in conjunction with A.P.Møller-Mærsk, DFDS, Arla, Danish Crown and DLG to use wind energy to produce ammonia. The production of ammonia is expected to start in 2026 and the capacity is sufficient to replace the current import of agricultural fertiliser in Denmark in addition to provide a green alternative to marine fuel, trucks and other heavy transport if ammonia gains acceptance as fuel in these sectors.

- HySynergy – A project by Shell and Everfuel to produce 1 GW of green hydrogen by 2030 combined with storage in Fredericia.

As Denmark only has limited industrial use for hydrogen, most will be used for e-fuels or exported. Denmark has an existing natural gas network connected to the European gas network in addition to connections to Norway and Sweden. These can be converted to hydrogen which will allow for a major export opportunity.

Iceland is in a unique position in being able to produce fully renewable e-fuels, including CCU and hydrogen for domestic use and even export due to the country's stable renewable energy sources, competitive power prices as well as the knowledge and experience gained in the field over the last decade or two. Iceland is contributing with extensive research and demonstration projects and has several past operations on hydrogen and e-fuels, for instance the hydrogen refuelling station for vehicles (Grjótháls, Reykjavík) that was operated by Skeljungur in 2003-2012. This was the world's first hydrogen refuelling station operated at a public gas station. The main purpose of the operation was for research and demonstration as well as a part of the EU funded ECTOS project.

Since the beginning of this century, two noticeable projects in research and the demonstration of the production of hydrogen by the electrolysis of water and its application to road transport have been initiated. However, the use of hydrogen in road transport is still minimal.

There are various projects under development for hydrogen and e-fuels/CCU in Iceland at the moment, although several cases have not been formally announced, such as in terms of technology providers. Several companies are planning to produce hydrogen by the electrolysis of water and distribute it for domestic applications. Landsvirkjun, The National Power Company of Iceland, is evaluating the feasibility of large-scale water electrolysis for domestic uses and not least export to the Netherlands.

2.2 E-fuels

E-fuels are produced by using power and either a CO_2 or nitrogen source. The electric power is used to produce clean hydrogen, as described above. The production pathways for three e-fuels with a relatively high technology readiness level (TRL) - methanol, Fischer Tropsch and ammonia - are described in the following together with the key points of where they can be utilised in specific Nordic countries.

> **Renewable methanol:** There are two production pathways for methanol. Either CO_2 and renewable hydrogen are used directly in the methanol synthesis, or the methanol is produced from a synthetic gas, also called syngas, containing mostly CO, CO_2 and H_2. Syngas can be produced by gasification e.g. of biomass. Methanol synthesis is a proven technology at TRL 9. A market for methanol already exists, as this is a bulk chemical used in the chemical industry, e.g. to produce plastics. However, on a larger scale, its utilisation as a transport fuel to substitute fossil-based fuels is more relevant. In today's vehicles, methanol can replace fossil-based fuels in gasoline engines with minimal modifications. The model range of Bi-fuel car models are rather limited. However, the modifications need acceptance by the car manufacturers, which might prevent this use.

> For shipping, methanol is considered an alternative to heavy fuel oil, and Maersk, for example, has ordered a methanol powered containership that will be launched in 2023. Stena Line has already operated a Ro-Pax ship (Stena Germanica) on methanol for several years (Stena Line, 2021).

> **Methanol-to-X**: Renewable methanol can further be converted to dimethyl ether (DME) or to renewable jet fuel through the Power-to-Liquid technology (PtL). For diesel engines, DME is a suitable alternative to fossil-based diesel. Both the methanol synthesis and the conversion to DME are commercially available at TRL 9, whereas the production pathway from methanol-to-jet fuel is at TRL 5. Further progress in the conversion of methanol-to-jet fuel is important for the future production of sustainable jet fuel. However, the process not only needs to be matured to TRL 9, the methanol-to-jet process also needs to be certified by the authorities that ensure the high standard of safety. There are already existing technologies for jet fuel production based on bio methane, for example, in terms of the gas-to-liquid technology.

> **The Fischer Tropsch process**: The syngas (hydrogen and CO_2 or CO) is converted to crude oil in the Fischer Tropsch process. The process has been used in large scale plants worldwide and is available at TRL 9. The crude oil from the Fischer-Tropsch process can be refined in a refinery to yield the desired fuel cuts for all purposes (light and

heavy road, marine and aviation). Jet fuel is already today certified to use 50% fuel based on the Fischer-Tropsch process, making it the fastest way to bring sustainable aviation fuel (also called jet fuel) to the market. However, the process has a significantly lower energy efficiency compared to the methanol to jet fuel process.

- **Renewable ammonia**: The production pathway for renewable ammonia is a single process using renewable hydrogen in combination with nitrogen, which can be obtained from the air. Both production of ammonia and air separation are at TRL 9. Today, ammonia is produced on a large scale for fertiliser production but relies on fossil-based hydrogen. The only difference between renewable ammonia and fossil-based ammonia is the source of the hydrogen. In addition to the existing use for fertiliser, renewable ammonia is also considered an option for marine fuel. Compared with heavy fuel oil, ammonia has the disadvantages of lower energy density, meaning that larger fuel tanks are needed, it is toxic and it burns slowly. The latter means that ammonia is not suitable for faster engines, but it is suitable for the slower 2-stroke engines used in the large container, tanker and bulk vessels which also have the space for larger fuel tanks. There is currently no engine on the market that uses ammonia, but the German company MAN Energy Solutions has one in development and expects that it will be ready in 2024. The advantage of ammonia is that it does not contain a carbon source and, therefore, emits no CO_2, but the engine might produce more NOx (a strong climate gas), which will require cleaning (scrubbing) the flue gas. Ammonia can also be used as a carrier of hydrogen molecules and converted into hydrogen before being fed into a fuel cell. However, this conversion uses energy.

The remaining part of this section is a description of the ongoing and upcoming e-fuel projects in each of the Northern countries.

In **Norway**, Statkraft, Finnfjord and Carbon Recycling International are developing a project for a commercial e-methanol project in Finnfjord in northern Norway. The plant will use raw CO_2 captured from the emissions of the Finnfjord ferrosilicon plant and hydrogen generated from the electrolysis of water using renewable electricity and has a planned production capacity of 100,000 tonnes of e-methanol per year by the end of 2023 (Statkraft, 2020).

Quantafuel is another Norwegian company carrying out projects for converting plastic waste to fuels. The produced fuel then needs to be upgraded in the refinement process to lower the amount of oxygen in the fuel and this process requires hydrogen as input (Quantafuel).

In **Finland**, a research project on electrofuels, funded jointly by Business Finland, VTT and the participating company partners, wants to make the technology that is being developed ready for scaling up. The project is public enterprise and a part of the Green E2 Ecosystem funded by Business Finland and administered by Clic Innovation. It is a continuation of VTT's PtX research, for example, the BECCU project launched in 2020 (Bioenergy International, 2021). The e-fuel project is also linked to the Green Electrification 2035-Veturi programme initiated by ABB. The project aims at combining hydrogen production through high-temperature of about 700°C electrolysis using a solid oxide electrolyser cell (SOEC) with carbon dioxide sequestration and Fischer-Tropsch fuel synthesis. It aims at a breakthrough for Finnish technology on the growing world market for synthetic fuels (Bioenergy International, 2021).

Sweden has several ongoing projects on CCU and electrofuels. There are plans to establish large-scale electro-methanol plants at Swedish pulp and paper mills and/or on combined heat and power plants. The company Liquid Wind also has a goal to build 10 electro-methanol plants in the Nordic countries by 2030 and is currently starting the front-end engineering design for an electro-methanol plant in Örnsköldsvik.

Denmark has plans for several large-scale projects to produce e-fuels. An example of such a project is the ammonia project in Esbjerg, a project by Copenhagen Infrastructure Partners in conjunction with A.P.Møller-Mærsk, DFDS, Arla, Danish Crown and DLG to using wind energy to produce ammonia. The production of ammonia is expected to start in 2026 and the capacity is sufficient to replace the current import of agricultural fertiliser in addition to providing a future green alternative to marine fuel, trucks and other heavy transport. The Danish maritime sector is very large and can play a key role well beyond Denmark and Scandinavia in setting the standards for fossil-free shipping.

In **Iceland**, CRI's (Carbon Recycling International) pioneering George Olah Renewable Methanol Plant (GO Plant) for the production of e-methanol was commissioned in 2011 and expanded in 2015 to a capacity of 4,000 tonnes per year - at that time, one of the largest water electrolyser installations in Europe and the leader in MW-scale electrolysis power of 6 MWel. The CO_2 used in methanol production is from geothermal steam wells. Since the beginning of the operation, most of the product has been exported to Europe.

Nordur is developing a power-to-gas pilot project at the Hellisheiði geothermal power plant, expected to come online in 2021/22. The installed water electrolysis power will be 25 MW and 100 GWh, which together with CO_2 from geothermal wells will be converted to e-methane, mainly for export to Switzerland.

The utilisation of CO_2 from Elkem's ferrosilicon plant in Grundartangi for large-scale e-fuel production has been the subject of several studies in the past 15 years and is currently being evaluated by several parties. The e-fuels in question are methanol, DME and Fischer-Tropsch diesel.

2.3 Bio-fuels and E-biofuels

Biofuels and e-biofuels are produced from biomass feedstock in combination with renewable hydrogen. Several production pathways are available at different TRLs and described in the following.

- **Pyrolysis, hydrothermal liquefaction (HTL) and hydrogenated vegetable oil (HVO):** These are all chemical processes that convert a biomass feedstock directly to a renewable crude oil. Renewable hydrogen is then used to upgrade the oil before it is distilled into a variety of fuels. Only HVO is at a fully commercial state (TRL 9), whereas pyrolysis and HTL are at TRL 5-7. Upgrading is required due to the high acid and oxygen content of the oil; the content must be lowered before the oil can be refined to diesel, petroleum and jet fuel. Both hydrogen consumption and end-product fuel distribution are highly dependent on the chosen process for fuel production and the composition of the biomass feedstock. The upgrading process for the biomass-based processes, pyrolysis and HTL, is only at TRL 5 and is thereby the bottleneck in the production pathway of bio oil. The potential is significant, as refining and upgrading make it possible to produce sustainable liquid fuels which are chemically identical to the fuels of today, i.e. they can be used without changes in engine technology.

- **Biogas and liquefied biogas (LBG):** An alternative utilisation of biomass is to produce biogas by a biological fermentation process which is commercially available at TRL 9. The biogas can be utilised directly as fuel in industry or converted to liquified biogas (LBG) and used as a marine fuel. Biogas is considered the renewable alternative to natural gas as it has almost the same properties both consisting mostly of methane, but it is currently more expensive.

The remaining part of this section is a description of ongoing and upcoming biofuel and e-biofuel projects in each of the Northern countries.

Norway has a significant potential for using forest residues as feedstock for e-biofuels. A Swedish-Norwegian joint venture Silva Green Energy has signed a contract with Danish Steeper Energy to build a large demonstration plant to produce e-biofuel based on forest residues from 50,000 forest owners (Statkraft, Silva Green Fuel is a collaboration between Statkraft and Sødra, formed in 2015 to develop and produce advanced biofuel to replace fossil fuels.).

Finland has a substantial forestry industry which produces bio-based carbon dioxide. Finland also has a lot of water, space for wind energy and engineering prowess in developing hydrogen technologies (Laaksonen, Aho, Silvennoinen, & Kortela, 2020). These developments may also be applicable in the other Nordic nations.

Sweden has several current projects in the area of e-biofuels, such as Perstorp's investment "Project Air", Preem's and St1's plans to increase biofuel production using fossil-free hydrogen and St1, Liquid Wind and Jämtkraft preparing for various investments in electric fuels. Another project is the GoBiGas project which is a demonstration plant for the production of biomethane from biomass via the gasification of woody biomass (Chalmers University of Technology).

Denmark has a large agricultural sector from which the residues (e.g. straw and manure) can be used as feedstock for e-biofuel production. Several development projects are ongoing both for pyrolysis (e.g. SkyClean) and hydro-thermal-liquefaction (e.g. Steeper Energy).

In total, the available (underutilised) renewable fuel production capacity in Denmark (9,300 tonnes of oil equivalent per year) is almost triple the current domestic production and more than 50% of the imported biofuels.

In **Iceland**, biomethane is produced by upgrading gas from the abandoned landfill site of the capital area, the new centralised organic waste treatment plant in Reykjavík, and the abandoned landfill site in Akureyri, by respectively SORPA and Norðurorka. The total production capacity of these installations is approximately 5.5 million Nm3 of biomethane annually, but currently, only 1.5 million Nm3 are utilised.

2.4 Carbon capture, storage and utilisation (CCUS)

Carbon capture and use is a way to reduce the CO_2 emission from processes with a CO_2 by-product. The captured CO_2 can be stored or used in combination with hydrogen to produce fuels, see Figure 2.1. The CO_2 is called biogenic if it originates from combustion or release from biomasses, as this is considered a cyclic process of CO_2-release and CO_2-uptake by the biomass. Other forms of CO_2 originates i.e. from combustion of fossil fuels, release of CO_2 from limestone in cement production or other processes that is not biogenic, including geothermic.

Four main technology tracks for carbon capture exist:

> **Oxyfuel** technology is based on combustion in oxygen diluted with recycled flue gas instead of using air. This produces a flue gas consisting mainly of CO_2 and water without nitrogen. The water vapour is easily removed, and the resulting gas with a CO_2 concentration of 70-85 vol% can then be further purified and compressed. The oxygen for combustion is produced by separation

from atmospheric air. The main challenge is to keep air leakages into the system to a minimum and retrofitting an oxyfuel installation will demand significant modifications to the existing plant.

- **Pre-combustion capture** involves separating fuel carbon from the combustible gases before combustion. This is, however, not relevant for retrofitting, but only gasification and reforming plants where the fuel is converted to CO_2 and H_2.

- **Post-combustion capture (PCC)**. CO_2 is separated from the flue gas combustion of fuel. This can be done by absorption in a liquid or uptake in a solid adsorbent which is subsequently heated, releasing the CO_2. Separation can also take place by means of membranes or extreme flue gas cooling (cryogenic separation). The post-combustion technology allows for shorter outages when retrofitting existing plants, and few modifications of the existing plant are needed. Furthermore, the process is suitable for treating flue gas streams with a CO_2 content of 3-20% at near atmospheric pressure. The difficulties are mainly related to the sensitivity to flue gas contaminants and high energy demand.

- **Direct air capture** technology takes the atmospheric air through a series of chemical reactions to extract the CO_2. However, due to the low concentration of CO_2 in the atmospheric air, the cost is high compared to the amount of CO_2 captured.

Currently, it is post-combustion technology which seems the most promising. Amine-based chemical absorption is the most mature technique for post-combustion capture. Among its sub-variants, the amine-based chemical absorption has the highest technological and commercial maturity. The amine gas treating consists of several processes that use aqueous solutions of various amines to remove hydrogen sulfide and carbon dioxide from gases.

Carbon can be captured from power plant, both fossil- and biomass based, where there is combustion, but it can also be captured from industries with high CO_2 emissions, e.g. cement production. Here, the combustion of the fuel used to reach the required temperatures emits a lot of CO_2, but also the chemical process itself releases a significant amount of CO_2. Likewise, the CO_2-emissions from refineries and the chemical industry are also significant point sources.

After capturing the CO_2, it could be transported from the site to the storage location via truck, ship or in pipelines. It may be possible to convert the existing pipelines for CO_2 transportation. The gas can either be compressed or liquified depending on the transportation method and size of the plant. An important addition to the CO_2 transport network is CO_2 clusters. Here, the CO_2 from smaller point sources can be stored before it is transported to the final storage location.

Geological storage of CO_2 is possible and proven both on- and offshore in depleted oil and gas fields. In Iceland, a particular opportunity exists to inject CO_2 in geothermal wells. Generally, the potential for storage varies between the Nordic countries. Underground storage of CO_2 has been in operation at the Sleipner field in Norway since 1996. Cooperation between the countries allows the transport of CO_2 and utilisation of the most feasible locations for geological storage. Another option for storage being investigated is the mineralisation of CO_2 in basalt (CarbFix project in Iceland).

The remaining part of this section is a description of ongoing and upcoming CCUS projects in each of the Northern countries.

In **Sweden**, there are many point sources of CO_2, of which many are biogenic as the fuel is biomass waste from the pulp and paper industry. The implementation of CCS and bioenergy carbon capture (BECCS) should be adopted to the local conditions at each site and in relation to the whole value chain. For the near future, Sweden is not planning any storage facility for CO_2, but the potential is being investigated. For ongoing projects, final storage outside of Sweden is currently the only solution. Consequently, the CO_2 must be liquified and transported to the final storage point. Sweden does not have natural gas pipe-routes to use for new infrastructure of CO_2 transport pipes. Therefore, the value chain in Sweden will most likely be based on a number of CO_2-hubs located at the coast where CO_2 is collected and exported by ship.

There are several planned and ongoing CCS projects:

> Stockholm Exergi – WTE (Waste to Energy) which has completed a pre-study and is expected to start engineering design of capturing, liquefaction, interim storage and out-shipment of CO_2 in Q2 2021.

> Preem Lysekil Refinery is carrying out a pre-study of capture, liquefaction, interim storage and out-shipment of CO_2, and Preem Gothenburg Refinery is carrying out a pre-study of capture and liquefaction.

> CinfraCap, a collaboration between Preem, St1, Nordion Energi, Renova, Göteborg energi and the Port of Gothenburg, is a pre-study project that aims at building a new CO_2-terminal or hub in the port of Gothenburg and includes liquefaction, interim storage and out-shipment of CO_2.

For **Norway**, the government's ambition is to realise a cost-effective solution for full-scale carbon capture, transport and storage (CCS) in Norway. The aim is to capture CO_2 from emission sources in Eastern Norway. The CO_2 will then be transported by ship to an onshore transport and storage terminal at Kollsnes on the Norwegian west coast. From the onshore terminal, CO_2 will be piped to a safe geological storage location under the seabed, close to the Troll oil and gas field (CCS Norway). The governmental CCS project, Longship has been approved by the Norwegian Parliament and funding is agreed upon.

Projects within Longship include:

- Norcem (subsidiary of Heidelberg Cement) has completed a front-end engineering design study in 2020 on capture, liquefaction, interim storage and out-shipment of CO_2. Norcem will capture CO_2 from its cement factory's flue gas at Brevik in Porsgrunn. When carried out, it will capture approximately 400,000 tonnes of CO_2 per year.

- With respect to CO_2 storage, the joint venture company Northern Lights JV (owned equally between Equinor, Shell and TotalEnergies) is planning a CO_2 transport and storage solution for a full-scale CCS project. The approved plan has the capacity to store 1.5 Mt of CO_2 annually (MTPA) and is planned to be carried out in 2020-25 (Equinor, 2019). The CO_2 transport and storage solution will start operating in 2024 and is planned with excess capacity. This means that, if the project is realised, other industrial emitters could capture and store their CO_2 without investing in the development of their CO_2 storage solution. Equinor and its partners could transport and store the industrial CO_2 for a fee. The option for a phase 2, which depends on international demand, has a planned annual capacity of 5 MTPA.

- Fortum Oslo Varme is planning to capture CO_2 from flue gas from its waste-to-energy plant at Klemetsrud in Oslo. The Norwegian Parliament's funding for the project is conditional on the basis of sufficient self-financing for the remaining NOK 3.8 billion from either the EU or any other source. If carried out, it will capture approximately 400,000 tonnes of CO_2 per year.

In **Finland**, no feasible geological storage has been identified in the northern part of the Baltic Sea. Finland will have to transport all the CO_2 it needs to store abroad, e.g. to Norway. Finland has a high proportion of biofuels with around 40% of their greenhouse gas emissions stemming from biogenic origins. This provides a high potential for BECCS (Nordic Council of Ministers, 2020).

Denmark has the potential for large scale CO_2 -storage both on- and offshore. It is estimated that the available underground reservoirs can store the current CO_2 emission in Denmark for 500 to 1,000 years. Denmark has not specified specific goals for CCS, but private investors are planning a CO_2 storage capacity of 4-9 million tonnes in 2030. There has been a public resistance to CCS onshore which results in most of the storage being planned for offshore. This favours industries close to the coastline and the storage reservoirs, as it will reduce the cost of transporting the CO_2.

Carbfix has for the last decade been at the forefront of research and development of CCS technology for mineralisation of CO_2 in basalt.

CCU is also investigated for using the captured CO_2 as feedstock for the production of renewable fuels. However, for the fuels to be considered renewable the CO_2 needs to come from renewable sources (wind or solar or biomass) also called biogenic CO_2. According to Dansk Energi, Denmark has almost 16 Mt per year biogenic CO_2 available today, compared to 49 Mt per year in the in total in the Nordics. A significant amount of the CO_2 in Denmark comes from imported solid biomass for energy use which is expected to be reduced towards 2050. Utilisation of the agricultural biomass in Denmark is, therefore, important to obtain a carbon source to produce renewable fuels. Another option is to capture CO_2 from point sources like cement production, which is impossible to decarbonise, as, otherwise, the current production method emits a significant amount of CO_2. This is due to chemical reactions releasing CO_2 and it is, therefore, a problem that is not solved only by changing the fuel for heating the process.

In **Iceland**, Carbfix has for the last decade been at the forefront of research and development of CCS technology for mineralisation of CO_2 in basalt. Today, considerable amounts of CO_2 (up to 12,000 tonnes annually) from ON Power's geothermal power plants in Hellisheiði have been successfully sequestrated. Pilot injections were carried out in 2012 at Carbfix's pilot site in collaboration with ON Power near the Hellisheidi geothermal power plant. In 2014, a full-scale capture and sequestration plant came online capturing 15% of the CO_2 emissions from the power plant, together with H2S. The capacity was doubled in 2016 to 10,000-12,000 tonnes of CO_2 per year. Using funds from the EU Horizon 2020 research programme, scientists are investigating the use of CarbFix technology near geothermal fields in Germany, Italy and Turkey, and elsewhere in Iceland where the bedrock is not basalt.

Carbon Iceland is planning a 1 million tonne per year direct air capture (DAC) operation in Húsavík by 2025 using Carbon Engineering's technology. The company states that the captured CO_2 will be used for e-fuel production and other industrial uses. A similar study on energy storage called the Icefuel project was conducted at Grundartangi industrial site (ferrosilicon and aluminium smelter).

ON Power will increase the proportion of CO_2 from the Hellisheiði geothermal power plant from 30% to 95% in 2025 using Carbfix's technology. The injected amount of CO_2 will be 33,000-35,000 tonnes per year. ON Power is also planning to use Carbfix's technology at the Nesjavellir geothermal power plant to inject 1,000 tonnes of CO_2 annually.

Climeworks will begin operating its Orca plant at Hellisheiði in 2021. The installation will capture 4,000 tonnes per year of CO_2 from the air, which will be mineralised with Carbfix's technology or liquified for other uses (Climeworks, 2021).

2.5 Renewable power and other input factors

Renewable power is essential as it can both be used for direct electrification or to separate water and thereby produce renewable hydrogen via electrolysis. Hydrogen can be used both as fuel to power electric motors via fuel cells or as an input to produce e-fuels and biofuels. Other resources, biomass, nitrogen or CO_2 may be used depending on the process.

In **Norway,** the electricity supply is green, renewable, reliable, flexible and cheap. Around 90% of the Norwegian production capacity is hydropower plants and 10% wind turbines. There are 1,000 water reservoirs, and the storage capacity corresponds to 70% of the annual Norwegian energy consumption. In the future, hydropower will only see a limited increase as few new hydropower are available. Furthermore, there is public opposition to the environmental impact of new hydropower plants. There is, however, potential for expanding the capacity of hydropower through upgrades and renewals and thereby integrate more fluctuating wind power. Some older hydropower plants could also be modernised to increase production by 10-20 TWh. Wind power production is expected to increase significantly, from 10 TWh in 2019 to 40 TWh in 2050. The Norwegian west coast has excellent onshore wind resources, but local opposition to onshore wind can reduce the potential development. Offshore wind will require the successful and cost-effective deployment of floating wind turbines, as the water is generally too deep for fixed foundations. One example is the floating wind farm project Hywind Tampen by Equinor. It has a capacity of 88 MW and is being planned 140 km off the Norwegian coast. Finally, solar power production is likely to see an increase in southern Norway but is not expected to play a major role.

In **Finland**, the electricity supply is a mix of hydro, thermal, nuclear and wind power. Wind power production is likely to increase significantly, as Finland has sufficient potential for wind-power electricity generation, both offshore and onshore. The challenge is that while the most suitable areas for wind-turbines installation are in the North of Finland, the majority of the existing hydrogen-producing facilities are located in the South, close to the industrial customers. Hydropower production is expected to be relatively constant, with no new facilities planned. Solar power will probably only play a minor role. Finally, nuclear power capacity will increase significantly with the commissioning of Olkiluoto 3 and Hanhikivi 1; this will provide CO_2-neutral power, albeit it may raise questions about the origin of the hydrogen produced based on nuclear rather than renewable power.

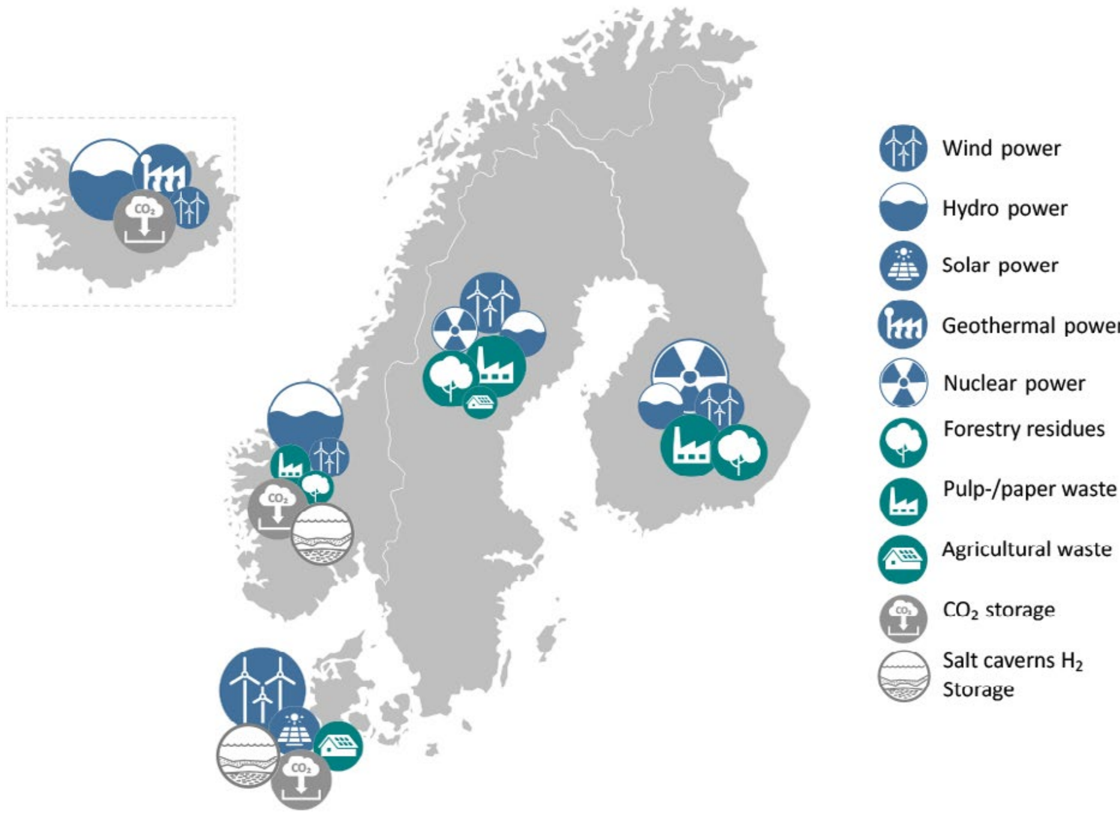
Sweden has an almost entirely decarbonised power system, achieved through investments in hydropower, nuclear power and district heating fuelled by biomass. In the future, wind power production is expected to increase significantly and solar slightly, whereas hydropower production is expected to remain constant with no new facilities being built. Finally, nuclear power production is likely to decrease, although there is significant uncertainty around its future.

In **Denmark**, the Danish electricity supply has a high share of wind power, biomass and coal. In the future, wind power production will increase significantly, especially offshore. By 2030, two energy islands will be built (in the North Sea and at Bornholm in the Baltic Sea) with a total capacity of 10 and 3 GW, respectively, and the possibility of later expansion. This will be an important step to harvest the world-class wind resources of the North Sea. Solar power production will increase, but not as much as wind power. In 2030, the production of wind energy is expected to be five times higher than solar power (forsyningssektoren, 2020). Finally, biomass-based power production is expected to be phased out gradually towards 2050.

In **Iceland**, 99.99% of all electricity is generated from renewable energy sources with small carbon footprints. Fossil fuels are only used in limited areas for backup power. In 2019, the total installed electrical capacity in the country was 2.9 GW and electricity production 19.5 TWh; 69% of all electricity was produced by hydropower plants, 31% by geothermal power plants and 0.03% by wind farms (Orkustofnun Data Repository, 2020). In the future, the wind power production is expected to increase while the geothermal will remain constant.

To sum up, Figure 2.2 provides a graphical representation of the energy supply, biomass availability and storage potential in each of the Northern countries.

Figure 2.2 Available energy resources and storage potential in the Northern countries. The size of the symbols is indicative of the availability in each country



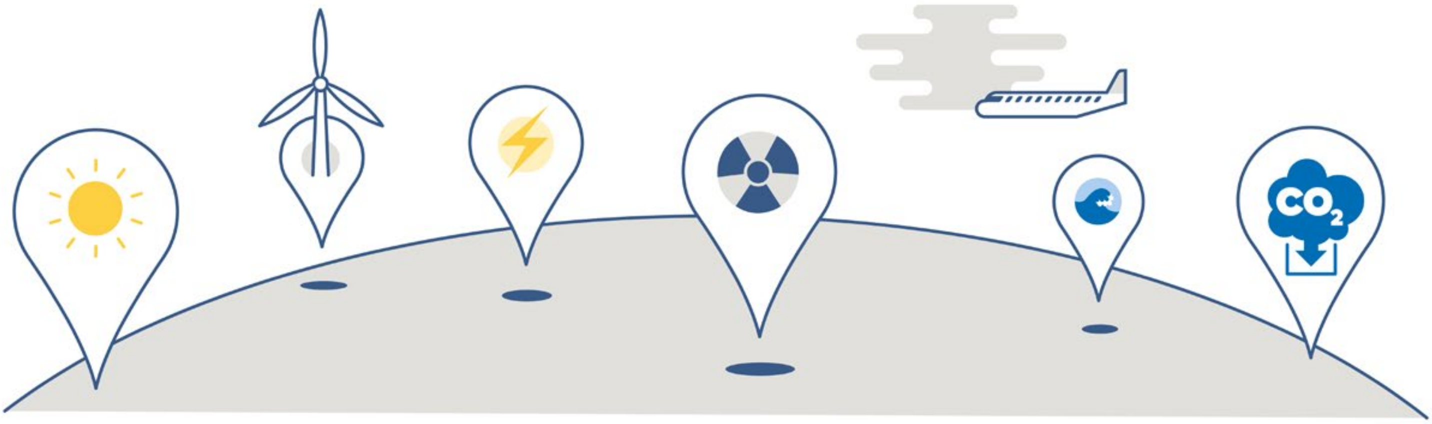
The share of wind power is expected to increase for all five countries. Sweden's power production will be affected by the discontinuance of nuclear power plants, while new, alternative energy sources will be of importance, whereas the remaining energy resources for power production will remain relatively constant. Synergies between hydro power plants and wind farms can increase their overall efficiency and provide an efficient energy storage. The exception is Finland, which is also expanding the use of nuclear power.

The available biomass resources are mainly located in the forest- and pulp/paper industry in Sweden and Finland, with a smaller amount available in Norway. Denmark has the potential to utilise agricultural waste as biomass, whereas a significant biomass potential has not been identified in Iceland.

Finally, the potential for hydrogen storage is primarily located in Norway and Denmark, where salt caverns can be used. For CO_2 storage, both Denmark and Norway are working on utilising their large potential for offshore storage in the North Sea. In Iceland, the potential for CO_2 storage in onshore by mineralising the CO_2 permanently in basalt or the Earth's crust. As both Finland and Sweden have not identified any specific CO_2 storage locations they will have to transport the captured CO_2 to the North Sea. Sweden, however, is investigating the potential for storage both permanent storage and storage for later use in the southern part of the Baltic Sea.

SHORT CONCLUSION

This chapter has addressed the developments within the technologies and their applications, which allow renewable power to be converted into sustainable electrofuels, using renewable hydrogen, CCU and bio-CCU. In addition, cost implications and the technology pathways for storing CO_2 has been discussed. In the next chapter, the international developments and market trends that promote the technologies internationally, together with the business/industry perspectives is addressed.



Chapter 3

INTERNATIONAL TRENDS AND DEVELOPMENT

The present situation and future needs for hydrogen, electrofuels, CCS and CCU in the Nordic countries are affected by international policies, global trends, current initiatives and markets outside the Nordic region. The number of governmental policies and private sector collaboration projects internationally on renewable hydrogen, e-fuels and CCUS technologies is growing quickly, focusing on developing and maturing the solutions to reaching GHG reduction targets in sectors where emissions are hard to reduce.

This chapter gives an overview of the significant international promotion of hydrogen, electrofuels, bio-CCUS and CCUS in other regions of Europe and important countries outside Europe with a focus on the international context driving development in the Nordic countries. First, EU initiatives are described. Then, the key trends in the hydrogen market, electrofuels and CCUS are identified. Finally, an overview of the global market development is given and relevant business models for renewable and low-carbon hydrogen are discussed.

3.1 EU initiatives

The European Commission has presented a plan to reduce EU greenhouse gas emissions by at least 55% by 2030, compared with the 1990 levels. In line with this, the July 2020 agreement between member states for a COVID-19 recovery and resilience facility under the Next Generation EU contains the requirement that member states draft national recovery and resilience plans in which 37% of funds are allocated to climate action (European Commission, 2021).

When the EU's hydrogen strategy was presented in early July 2020, Frans Timmermans, European Commissioner for Climate Action, stated that "Clean hydrogen is one of the top priorities in our energy transition", and one of the EU's key instruments for phasing out fossil fuels and making the transition to a climate-neutral era. Large-scale deployment of clean hydrogen is seen as a key for the EU to reach its reduction targets (European Commission, 2020). Investment in hydrogen is also expected to foster sustainable growth and create jobs. The Commission's recovery plan also stresses clean hydrogen as one of the essential subjects to address to unlock investment in clean technologies and value chains (European Commission, 2020).

The hydrogen strategy has several clear ambitions towards climate neutrality in 2050. From 2020 until 2024, the objective is to install at least 6 GW of green hydrogen electrolysers in the EU, and a capacity for production of up to 1 million tonnes of green hydrogen per year. From 2025 to 2030, the objective is to install at least 40 GW of green hydrogen electrolysers by 2030 and produce up to 10 million tonnes per year of green hydrogen (European Commission, 2020). A further 40 GW is expected as imports to the EU (European Commission, 2020). At this point, hydrogen is expected to be part of an integrated energy system, and steps will be taken to transport hydrogen from areas with large renewable potential to demand centres located possibly in other Member States, as part of an EU-wide logistical hydrogen infrastructure (European Commision, 2021). This pan-European grid, including a

> The ETS Innovation Fund, which will pool together around €10 billion to support low-carbon technologies in the period 2020-2030, has the potential to facilitate demonstration projects on hydrogen-based technologies.

network of hydrogen refuelling stations will need to be planned.[2] From 2030 to 2050, green hydrogen technologies should reach maturity and be deployed at large scale to reach all the hard to decarbonise sectors, and about a quarter of renewable electricity might be used for green hydrogen production.

To achieve this, the EU plans to promote investments and actions in support of the hydrogen supply chain. Through the Clean Hydrogen Alliance, the EU will simultaneously facilitate cooperation in a range of large investment projects, including IPCEI (Important Project of Common European Interest) projects, along the hydrogen value chain.[3] Finance for support to hydrogen investments is also expected to be mobilised through the recovery instrument Next Generation and the EU sustainable finance strategy and the EU sustainable finance taxonomy. Under the Research and Innovation framework Programme Horizon Europe, an institutionalised Clean Hydrogen Partnership has been proposed with focus on renewable hydrogen production, transmission, distribution and storage, alongside selected fuel cell end-use technologies. In addition, the ETS Innovation Fund, which will pool together around €10 billion to support low-carbon technologies in the period 2020-2030, has the potential to facilitate demonstration projects on hydrogen-based technologies. The Commission will also provide targeted support to build the necessary capacity for the preparation of viable hydrogen projects.

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2 The existing gas grid could be partially repurposed for the transport of renewable hydrogen over longer distances and the construction of larger-scale hydrogen storage facilities would become necessary.

3 The specific IPCEI instrument enables state aid to address market failures for large cross-border integrated projects for hydrogen and fuels derived from hydrogen that significantly contribute to achieving climate goals.

The Commission also plans to introduce EU-wide instruments for a policy framework in support of the carbon emission reduction benefits of hydrogen. This would include a common low-carbon threshold/standard for the promotion of hydrogen production installations based on their full life-cycle greenhouse gas performance. In addition, it will define a comprehensive terminology and Europe-wide criteria for certification of renewable and low-carbon hydrogen (European Commission, 2020). The EU already has the basis for such a supportive policy framework, notably with the Emission Trading System (ETS) and the Renewable Energy Directive (European Commission, 2020).

The Emission Trading System (ETS), as a market-based instrument, provides a technology-neutral, EU-wide incentive for cost-effective decarbonisation in all its covered sectors through carbon pricing. The EU ETS works on the 'cap and trade' principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. Within the cap, installations buy or receive emission allowances which they can trade with one another as needed. The limit on the total number of allowances available ensures that they have a value. Trading brings flexibility that ensures emissions are cut where it costs least to do so. After each year, an installation must surrender enough allowances to cover fully its emissions; otherwise, heavy fines are imposed. The cap is reduced over time so that total emissions fall. The ETS operates in all EU countries and in Iceland, Liechtenstein and Norway (EEA-EFTA states) and limits emissions from around 10,000 installations in the power sector and manufacturing as well as from airlines operating between these countries.[4] It covers around 40% of the EU's greenhouse gas emissions. To achieve climate neutrality in the EU by 2050, including the intermediate target of an at least 55% net reduction in greenhouse gas emissions by 2030, the Commission is proposing to revise and possibly expand the scope of the EU ETS (European Commission, 2020). Furthermore, the Commission seeks to complement the ETS with a revised Effort Sharing Regulation (ESR), which is expected to determine carbon reduction levels for non-ETS sectors at 40% (European Parliament and Council Regulation 2018/842).

The renewable energy directive covers, among others, the shares of renewable energy within the total energy production and transportation. The directive establishes mandatory national targets consistent with a

4 The industries covered are: Electricity and heat generation; energy-intensive industry sectors including oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals; commercial aviation within the European Economic Area. Almost all the existing fossil-based hydrogen production is covered by the ETS, but the sectors concerned are deemed to be at a significant risk of carbon leakage and therefore receive free allocation at 100% of benchmark levels. As foreseen in the ETS Directive, the benchmark used for free allocation will be updated.

20% share of total energy from renewable sources and a 10% share of energy from renewable sources in transport in EU energy consumption by 2020 (European Parliament and Council Directive 2009/28/EC). All types of energy from renewable sources consumed in all forms of transport shall be taken into account. Since the renewable energy potential and the energy mix of each Member State vary, the Community 2)% target is translated into individual targets for each Member State. The 10% target for transport applies for all member states (European Parliament and Council Directive 2009/28/EC).

Fuel for transportation is also regulated through the Fuel Quality Directive (FQD) which sets quality requirements to reduce greenhouse gas and air pollutant emissions, establish a single fuel market and ensure that vehicles can operate everywhere in the EU (European Parlament and Council Directive 2009/30/EC, 2009). The directive applies to fuels such as petrol, diesel and biofuels used in road transport and gasoil used in non-road-mobile machinery. The FQD requires a reduction of the greenhouse gas intensity of transport fuels by a minimum of 6% by and after 2020. The FQD is currently under review.

Finally, the EU regulation on CO_2 emission performance standards for cars and vans sets EU fleet-wide CO_2 emission targets (European Parliament and Council Regulation 2019/631). The regulation, applying from 2020, 2025 and 2030, was recently reviewed and includes a mechanism to incentivise the uptake of zero- and low-emission vehicles. The current EU fleet-wide average emission target for new cars is 95 g CO_2 /km and 147g CO_2 /km for new vans. These requirements have a major impact on emissions in Sweden, as they affect the Swedish vehicle manufacturers that sell vehicles in the EU, and thereby also considerably affect the composition of the vehicle fleet (Ministry of the Environment, 2020).

3.2 International trends

As in the EU (listed above), governments across the world are increasingly seeing renewable hydrogen, e-fuels and CCUS technologies as promising technologies for tackling the challenges and reaching their GHG reduction targets.

In the last few years, the world has seen an increase in private sector initiatives that focus on improving technologies and establishing full value-chain collaboration. These initiatives often grow out of public or sector investments. The initiatives often go hand in hand with research programmes and public framework strategies and are likely to lower production costs and transaction barriers.

Following the public and private sector interest in the technologies, significant investments are planned within the next couple of years

> The decreasing overall ETS cap further increases the incentives for storage as it puts a monetary value on stored fossil CO_2.

throughout the world. All investments currently hinge on the need for de-risking (through clarity on economic incentives, prices and actual offtake etc.). More available financing will lower the risks and cost of the development of a full supply chain.

Significant cost reductions in the key technologies are lowering the overall production price of renewable, low-carbon hydrogen. Renewable energy-based electrolysis has seen significant cost reductions because of cheaper renewable energy and improvements in the longevity and efficiency of electrolysis equipment. According to the Hydrogen Council, this effect is likely to reduce the overall production cost of renewable hydrogen with 60% by 2030 compared with the 2020 baseline (Hydrogen Council, 2021).

Electrolysers are improving quickly which increases the possibilities for scaling up the processes from megawatt to gigawatt. This will reduce the production costs.

An international transportation infrastructure that can lower the cost of port-to-port transport and interconnections between larger regions are slowly being established. An example is the international collaboration on the European Hydrogen Backbone, which is an initiative for a dedicated hydrogen pipeline transport network spanning ten European countries, on behalf of eleven European gas infrastructure companies.

Moreover, clean hydrogen represents an increasingly attractive feedstock for industrial uses (e.g. production of steel and chemicals such as ammonia and methanol). There are currently 90 industrial-scale projects across the globe (Hydrogen Council, 2021). Hydrogen production could turn into the largest electricity customer, doubling power demand in Europe.

The current trends in the market for Carbon Capture is linked to permanent carbon storage to ensure that climate targets are reached. By reducing CO_2 emissions through storage, industry and the energy sector can reduce the strains of the Emission Trading System (ETS). The decreasing overall ETS cap further increases the incentives for storage as it puts a monetary value on stored fossil CO_2. ETS, which through its "cap and trade" system for CO_2 emissions is the existing market for carbon, could also include sectors for negative-emission technologies in the future. This also involves the Effort Sharing Regulation, which covers the sectors not included in the EU ETS. Both mechanisms would create a market for captured CO_2 of biogenic origin and further incentivise investments in this technology.

Future demands for electrofuels will presumably add significantly to this. Captured carbon (preferably from a biogenic source) currently seems to be needed for the production of the more advanced electrofuels for use in for example air transport. Coinciding with increasing demand for CO_2 for electrofuel production, will be the diminishing of the current most effective point sources for carbon capture. This is due to the expected strongly reduced the use of fossil fuels, e.g. in power plants and production sites. Electrofuel production will thus have to rely on remaining point sources for biogenic carbon (i.e. biomass fired powerplants) or the much less efficient solutions for capturing CO_2 directly from atmospheric air.

3.3 Global hydrogen and carbon capture market

The demand for hydrogen has grown threefold since 1975. The world currently produces over 70 Mt of hydrogen per year, which to a large extent is consumed by the petrochemical industry. Currently, over 96% of the total consumed hydrogen is produced from fossil fuel, and less than 0.1% of global hydrogen production is water electrolysis. Taking into account that the market for CO_2 so far mainly has been limited to appliances in the food industry, significant developments are to be envisaged in the coming years.

Germany currently has the highest usage of hydrogen in Europe at more than 70TWh (more than one-fifth of the European total). The UK and Netherlands use natural gas extensively in heating which in the future will be converted to hydrogen. France, Spain and Portugal could emerge as leaders in clean hydrogen production. The plans for the development of the area are significant and the targets ambitious and facilitated by a rapid and extensive rollout of solar and wind generation capacity.

In the European industry, the use of hydrogen is well-established. Hydrogen use in ammonia production, refining, and methanol production together represents 91% of the current hydrogen demand:

- **Refineries** are the largest consumers of hydrogen in Europe, accounting for 45% of the current hydrogen demand
- **Ammonia production** is the second largest consumer with 54% of EU's production capacity in four countries: Germany, Poland, the Netherlands and France
- **The methanol industry** is the third largest consumer in Europe, concentrated in Germany, the Netherlands and Norway
- **Steel industry** with Germany covering over 30% of EU's production volume (World Steel Association, 2019). Small scale hydrogen projects in the steel industry have started in Germany, Sweden and Austria

Perspectives for the usage of hydrogen over the coming years are significant:

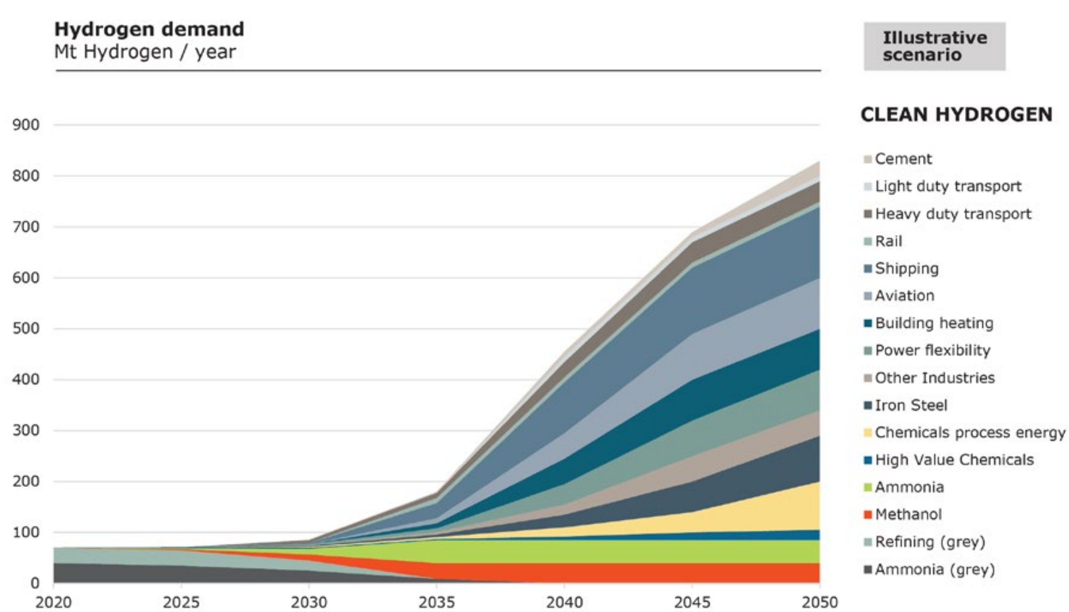
- In **transportation**, hydrogen can play a key role, either via the direct use of hydrogen in fuel cell-powered cars, trucks, buses, trains and ships or through the production of hydrogen-based synthetic liquid fuels for the shipping and aviation sectors.
- **Road** – Sweden brings good examples of the use biogas for transport in urban areas. Due to its higher energy density compared with batteries, fuel cells are an option for larger vehicles.
- **Rail** - depending on local conditions, fuel cell trains can be less expensive than electrification and can operate for a long time without refuelling. Already by 2030, 30% of diesel trains could be replaced with fuel cell trains.
- **Shipping** – the international shipping sector is a significant consumer strongly dependent on fossil fuel oil and it does not fall under national climate agreements. Smaller ships mostly run on diesel fuel. The largest part of the shipping sector will depend on low-carbon liquid fuels, including biofuels (e.g. advanced biodiesel), hydrogen and derived fuel, while smaller ships could be electrified.
- **Aviation** - international aviation accounts for 89% of the total energy use in the aviation sector, with the remainder attributable to domestic flights (which are covered by national climate policies). Electrification is not an option for larger planes. Liquid biofuels and synthetic fuels produced from hydrogen seem to be the most suitable low-carbon fuels.
- In **buildings**, renewable and low-carbon hydrogen could be an option for the decarbonisation of neighbourhoods connected to the gas grid, where building stock is old, and upgrades of the existing buildings are difficult or very costly.

The global market for hydrogen has the potential to reach EUR 10 trillion by 2050, whereof EUR 2.2 trillion alone in Europe, EUR 2.9 trillion in the US and EUR 4.4 trillion in Asia (Goldman Sachs, 2020). In comparison, the world wind energy market was estimated to about EUR 105 billion in 2000 (Wind Energy Market Share Analysis | Growth Forecasts 2027). Other market studies suggest that hydrogen could be a EUR 120 billion+

industry in Europe by 2050 as the demand is expected to grow from 327 TWh today up to 2,500 TWh by 2050 (Aurora Energy Research, 2020). Outside of Europe, the hydrogen supply is expected to come from locations with strong solar and wind resources such as Australia, Chile, North Africa and the Middle East. Low-cost hydrogen could lead to global trade and connect to future major demand centres such as the EU, Japan and South Korea.

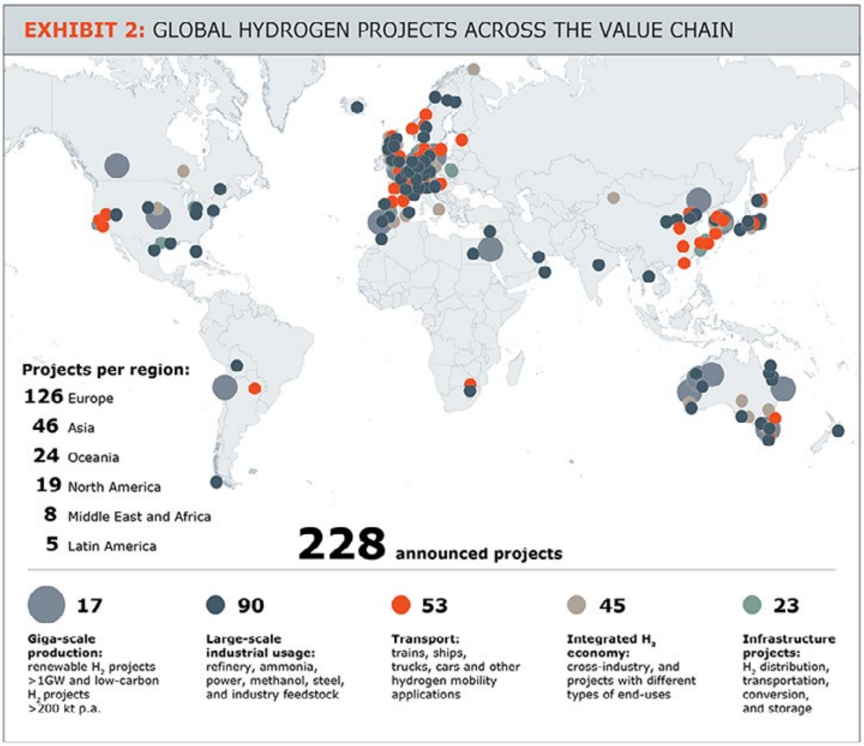
A study conducted by the Energy Transitions Commission (a global network of energy industry leaders), with inputs from SYSTEMIQ, BloombergNEF, McKinsey & Company, IRENA and the IEA, among others, describes a potential scale-up scenario of the global hydrogen economy. The scenario supposes a reduction in the demand for fossil-based hydrogen towards 2035 as well as an increase in the hydrogen demand by 1,500% in 2050. Notwithstanding the many uncertainties, the report demonstrates a significant market potential for hydrogen and hydrogen-based products (Energy Transitions Commission, 2021).

Figure 3.1 Potential scale-up of the hydrogen economy in the world



Source: SYSTEMIQ analysis for Energy Transitions Commission (2021)

Figure 3.2 Global distribution of hydrogen projects across the value chain



Source: Hydrogen Council, McKinsey & Company (2021)

At the beginning of 2021, over 30 countries have published hydrogen road maps, the industry has announced more than 200 hydrogen projects and ambitious investment plans, and governments worldwide have committed more than USD 70 billion in public funding. The costs of hydrogen production, transmission, distribution, retail and end use are falling thereby creating a momentum in the entire value chain (Hydrogen Council, 2021).

In both Norway and Denmark, the potential magnitude of the market for captured CO_2 in the coming years has been assessed. According to the plan for the long-term use of the Northern Light's infrastructure in Norway, the current project design aims at a capacity of up to 5 million tonnes per year. Scenarios have been presented by Equinor operating with both 20 and 100 million tonnes, including offtake from CO_2 sources reaching beyond the Nordics, Poland, the Netherlands, Northern Germany and the UK, thus also including the Baltics and Southern Europe (Equinor, 2019). Similarly, the Danish Government has conducted market analyses of the potential demand for storage primarily from Finland, Sweden and Germany showing a potential of up to 40 million tonnes (Klima-, Energi- og Forsyningsministeriet).

3.4 Business models for renewable and low-carbon hydrogen

As described hereinabove, the market potential for renewable and low-carbon hydrogen, e-fuels and CCUS seems staggering and possibly on the verge of a significant breakthrough. Still, uncertainty characterises the business models for renewable and low-carbon hydrogen.

Even though signals from both public and private stakeholders are strong, uncertainty around key indicators crucial for the financial due diligence prevent the final decisions for the needed large-scale investments.

As society as a whole is in the beginning of a transition towards a partly hydrogen-based economy, key investment information such as the likely size of demand and the price of renewable and low-carbon hydrogen is still very unclear. The need for a green transition in industry and transportation is a strong driver as is the planned feedstock production but the uncertainty hampers large scale projects beyond the planning stage.

This is clear, for example, with the hydrogen strategy from Fossil Free Sweden and a current Danish road map for Green Fuels for Industry and Transportation developed by research and industry stakeholders (2021). Here, de-risking investments in production, storage and transmission capacity are a clear focus and a barrier for further development of a hydrogen market. At the same time, significant investments are needed to scale up production and reduce the cost of clean hydrogen.

Several remedies can be considered in providing a basis for the development of a hydrogen economy in a scale that enables investment. For example, by pooling offtakers it is possible to generate orders for hydrogen and electrofuels in quantities that make large scale production more viable. New ways of cooperation along the value chain also apply, where both producers and offtakers align their ambitions and expectations as well as jointly invest.

Currently, it is assumed by leading Nordic consumers of fuel that the willingness to pay a premium for using clean fuel in some cases is limited. With SAS, it is possible, for example, to request biobased fuel when booking a flight, but this option is in low demand according to sources in the industry. Even though business-to-business services are thought to be more willing to pay (for example in shipping), it is a clear indication that the end consumers must be considered in the creation of a hydrogen-based market.

Public framework conditions must be favourable if private stakeholders are to be successful in developing viable business models for renewable and low-carbon hydrogen. Provisions of some sort of economic incentives to producers are useful for de-risking for investors. In Denmark, a contractual regime (CfD – Contract for Difference) has been applied with success in relation to the development of offshore wind farms. In a report published in the autumn of 2020 for the UK Government by the Department for Business, Energy & Industrial Strategy (2020), four regulatory models are proposed to overcome these needs originating from non-viable, immature markets for renewable or low-carbon hydrogen. These models are:

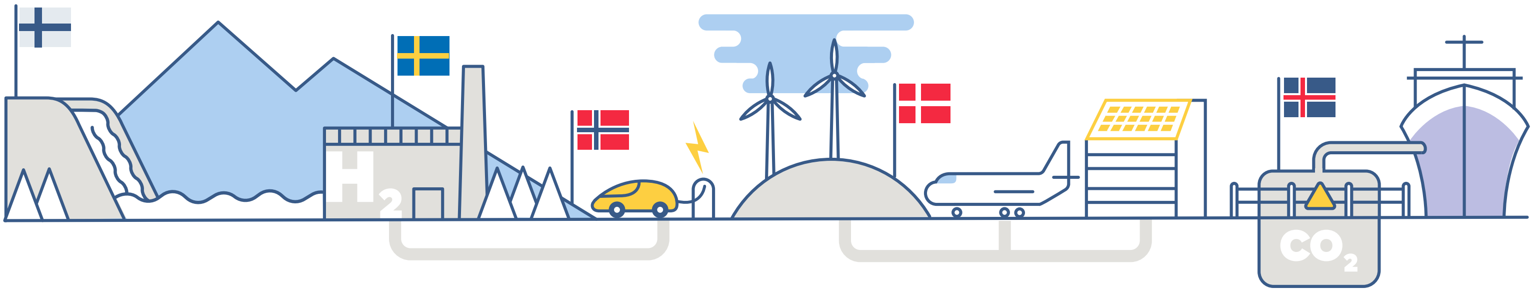
- Contractual payments – The producer receives a subsidy to cover the excess cost of renewable or low-carbon hydrogen relative to conventional. This model will close or narrow the gap between renewable or low-carbon hydrogen and other fuel solutions through subsidies.
- Regulated returns – Ensuring the producers a regulated return on their costs. This includes cap-and-floor models and a regulated asset base.
- Obligations – Placing demands on fuel suppliers or end-users, for example, on the usage of green hydrogen.
- End-user subsidies - An ongoing technology-neutral subsidy to end-users for carbon abatement.

Of the above, the most favourable models are contractual payments to producers and regulatory returns models, as contractual models can give more certainty to producers, while regulatory models may be easier to implement, given the existing institutional capabilities. Incentivising the use of green hydrogen and end-user subsidies or obligations is more challenging as it leaves significant policy-driven risks with producers.

Other public policies for improving the business models could be to ensure a minimal cost for taxpayers, to strive towards simplicity in model design, compatibility towards a wider value chain – which is not accustomed to close cooperation and, finally, a model that naturally leads to a market free of subsidies.

SHORT CONCLUSION

This chapter has addressed the international developments and market trends that promote the technologies internationally, together with the business/industry perspectives. The following chapter identifies the energy and climate benefits as well as environmental risks for the Nordic countries to involve in the development and implementation of the technologies.



Chapter 4

NORDIC BENEFITS AND RISKS

This chapter describes the benefits and risks for the Nordic countries to involve in the development and implementation of the technologies. This includes the energy and climate benefits of implementation of the technologies in different sectors and an overview of the environmental impacts and risks.

Sector benefits of implementation of the technologies in an energy perspective.

In an energy perspective, there are multiple benefits of implementing renewable and low-carbon hydrogen and electrofuel production, mainly related to the improvement of system flexibility and the enabling of sector coupling. The energy storage opportunities of these production facilities offer to delay the use of energy to a later time than when it was generated and, therefore, decouples the supply and demand of energy. For this to happen, the sector stands before a transformation as it adapts to the increased renewable energy and the introduction of the hydrogen value-chain of renewable and low-carbon hydrogen, electrofuels and carbon capture, across all the energy producing and consuming sectors. The benefits will increase if the strengths of the individual system are utilised for the optimal implementation of the technologies, while also ensuring efficient interfaces between the different energy sources into the energy systems.

As described in chapter 5, the development of infrastructure related to hydrogen production and carbon storage, including offshore grids and energy islands, has already been initiated in the Nordics. Now, the balancing between the increasing renewable share with electrofuel flexibility and the associated energy storage capacity (e.g. hydrogen storage) must be fully understood together. Opportunities must also be explored for developing hybrid plants combining renewable hydrogen and e-fuel production with energy storage, wind turbines, and solar panels as well as integrating power infrastructure and waste heat surplus to district heating.

> The most cost-efficient decarbonisation happens through direct electrification, and thus the other technologies should mainly be used when this is not a viable option. Therefore, hydrogen, electrofuels and CCUS may be used to reduce emissions in hard-to decarbonise sectors, such as parts of transport and industry.

Sector benefits of implementation of the technologies in a climate transition perspective.

The most cost-efficient decarbonisation happens through direct electrification, and thus the other technologies should mainly be used when this is not a viable option. Therefore, hydrogen, electrofuels and CCUS may be used to reduce emissions in hard-to decarbonise sectors, such as parts of transport and industry. The degree to which these sectors are hard to decarbonise vary across the Nordic countries.

The benefits within industry vary depending on the output of the industrial sectors in each country. In Finland and Sweden, heavy-energy industrial processes within the steel industry may be decarbonised using hydrogen, which is expected to have large consequences on climate emissions in these countries. Contrarily, in Denmark, most industrial activities can be electrified, although some energy-intensive production (primarily cement production) mechanisms will still need methane (most likely biogas) in production. This also applies for Swedish cement production. Hydrogen and electrofuels are thus not relevant options for these industries. On the other hand, the use of CCUS technologies may have a significant impact on the cement industries, which are among the largest emitters.

The transportation sector is traditionally also a hard-to-decarbonise sector, where advances are preconditioned by the already-made investments in engine technology. Within transport, most Nordic countries see potential for the hydrogen use within heavy transport and short-distance shipping. One precondition for this is a hydrogen filling infrastructure along the main road network and ports. In the long run, most light vehicles are expected to be electrified. For both types of road transport, there is potential for use of electrofuels in an intermediate perspective, directly in the existing vehicles. In Norway, where the transformation to electric vehicles is already underway, the climate benefits of this transition would be lower than for instance in Denmark, where there are few electric vehicles today.

There is also a considerable potential for climate benefits using electrofuels within heavy ocean shipping, which are large sectors in Denmark and Norway. International shipping is, however, not part of the national or international reduction requirements. Although no less relevant from a climate perspective, it means that the reductions do not count in either of the reduction schemes and, therefore, might be less politically desirable. The same applies for aviation, which is considered a particularly hard-to-decarbonise sector, with large benefit potentials from electrofuels. For Copenhagen Airport, the largest airport in the Nordic countries with considerable international bunkering, the climate potential is particularly high. In a national perspective, for the Nordic

countries with high levels of domestic aviation (Sweden, Norway and Finland), these climate benefits will also count as part of the national reduction requirements.

Use of electrofuels within agriculture is also a viable option for agriculture heavy areas in Denmark and southern Sweden. Ammonia is already used for land fertilisation, which could technically but not financially be easily replaced by renewable or low-carbon ammonia.

Finally, there are potentials for the use of hydrogen and electrofuels within heating, due to synergies in production. For instance, district heating plants located close to e-fuel plants are likely to have a possibility to utilise surplus heat. The amount will depend on the specific temperatures of the e-fuel processes.

The potential for CCU is connected to the potential for production of electrofuels, as carbon is used as input in methanol production. In particular, there appears to be a considerable potential for CCU as input to the large methanol production in Norway, while e-methanol production is also well under way in Denmark and practised for many years in Iceland by CRI.

At first glance, the capture of both biogenic and non-biogenic carbon has almost unlimited potential across the Nordic countries. However, the future potential of carbon capture must be weighed against the demand for biomass (and hence carbon) for fuel production to satisfy the aviation industry. As such, the potential for CCU and CCS are linked. CO_2 storage is most likely to be located on the continental shelf of either Norway or Denmark, where conditions are good, and the capture is very viable in the North Sea and Iceland.

Environmental and health risks

There are environmental risks related to both production and use of technologically advanced energies as hydrogen and electrofuels. The environmental benefits of producing green hydrogen and electrofuels depend on the availability of renewable electricity. Electrolysis is a power-intensive technology, which leaves a low energy production efficiency in comparison to currently available technologies. The processes will, therefore, only make socially and environmentally sense if the used electricity production replaces conventional fossil energy production and does not have alternative technology opportunities with a higher energy efficiency. Smart use of the technologies, which does not displace other, more effective solutions, is a prerequisite for the environmental impact.

Furthermore, water is a prerequisite for the electrolysis process. The country average non-agricultural water scarcity factors for Nordic countries are all low in comparison to European and Global average (NER, 2020), implying that the use of water in the electrolysis process will not pose a problem in the region. However, the availability depends on

the location of the production plants for hydrogen production.
The use of advanced energies also poses environmental risks. For instance, in the maritime sector, the conversion to e-ammonia is thought to reduce CO_2 emissions. However, as the engines are still under development, it is unclear how much nitrous oxide (laughing gas) will be emitted.

Regarding CCUS, the origin of the CO_2 is important for understanding and accepting the environmental benefits and related risks. While the capture of biogenic CO_2 is generally accepted, there is still some scepticism towards the capture of fossil CO_2. The argument brought forward concerns the danger of prolonging fossil fuel production by allowing fossil CO_2 capture, although most political parties and organisations accept the necessity of the CCUS to reach the climate goals.

Moreover, the transport and storage of CO_2 has a risk for CO_2 leakage. In July 2020, the European Commission agreed that the capture facilities will be able to subtract CO_2 from their emissions accounting when CO_2 is transferred from the ship to the reception terminal. However, a facility may not subtract allowances for CO_2 that leaks during transport and must thus surrender allowances for these emissions. For this reason, each capture facility should have detailed and implemented monitoring plans developed in consultation with relevant national authorities to regulate leakage and emissions of CO_2 during transport (Norwegian Ministry of Petroleum and Energy, Meld. St. 33, 2020).

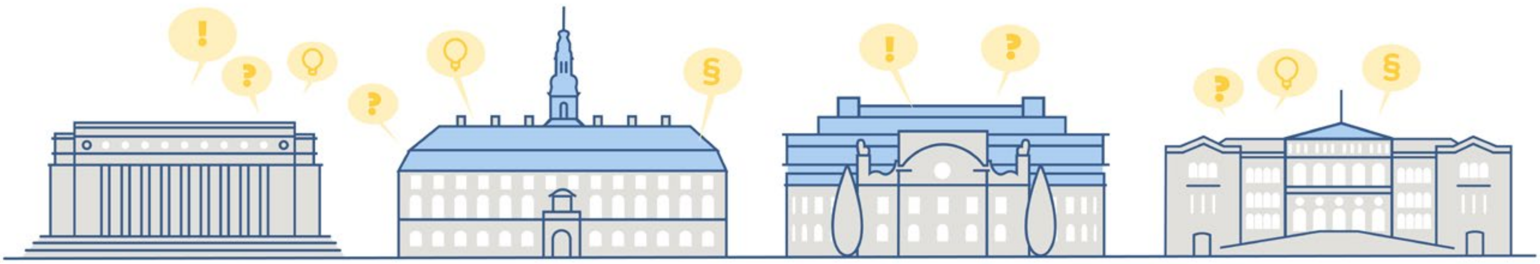
Underground storage of CO_2 was initiated at the Sleipner field in Norway in 1996, and since then a steady stream of insights from this project have been generated. Yet, the long-term implications of storing carbon in the underground can be further explored. This is a matter of ensuring that the CO_2 remains isolated from the atmosphere in the long term and that the capture, transport and storage elements do not present other risks to human health or ecosystems. The CCS Directive on the geological storage of carbon dioxide constitutes the legislative framework for the environmentally safe storage of CO_2 within the EEA (European Parliament and Council Directive 2009/31/EC). Four conditions for safe storage can be found in the CCS directive. The first condition is that all available information indicates that the stored CO_2 will remain completely and permanently contained. The second is that a minimum period determined by a relevant authority has elapsed before the monitoring of the storage site ceases. The third condition is that the financial obligations related to monitoring and risk management have been fulfilled. The fourth condition is that the storage site has been cautiously abandoned and the injection facilities removed. Due to the storage risks, several Nordic countries have seen public resistance to CCS onshore which may result in most of the storage being done offshore.

In essence, while the directive addresses damages and risks related to environmental issues and to person and property, it does not sufficiently address the challenges of climate change.

If a carbon capture technology is applied, it must result in processes with neutral or negative emissions to make sense. However, even if the processes theoretically make environmental sense, many elements must be ensured. If the amount of atmospheric CO_2 capture and fixation is equal to other fossil emissions over the life cycle, the process is carbon neutral (Müller, 2020). In all other cases, CCU technologies have positive CO_2 emissions over the life cycle. Still, emissions can be lower than for competing conventional processes. In this case, the CCU process also contributes to climate change mitigation through substitution, and hence is carbon reducing.

SHORT CONCLUSION

This chapter has addressed the energy and climate benefits and environmental risks for the Nordic countries to involve in the development and implementation of the technologies. The next chapter covers the framework conditions for this development.



Chapter 5

NORDIC POLICIES AND MEASURES

This chapter gives an overview of relevant political goals, research and market framework conditions, and the enablers and critical barriers in each of the Nordic countries as well as cross-Nordic initiatives. This includes public funding of research, innovation and end-to-end pilot and demonstration projects as well as measures directed at creating a market for production and offtake. Finally, other existing policies which indirectly affect the conditions for implementation are highlighted as an enabling factor or an obstacle.

All of the Nordic countries have high climate ambitions and are working rapidly to cut emissions through political goals, support measures and policies aiming at changing incentives in order to achieve carbon neutrality. The Nordic countries have all set fixed targets for reducing their emissions with a common goal in their climate acts of becoming low-carbon or carbon neutral societies by 2050. Although the Nordic countries have different access to natural resources, geological formations and political, societal and technological readiness, they all regard hydrogen, electrofuels and CCUS as important elements.

5.1 Norway

5.1.1 Political goals for the development of hydrogen, electrofuels, bio-CCUS and CCUS

Norway has a clear ambition to reduce GHG emissions by 50-55% from 1990 levels by 2030, and to transition into a so-called "low emission society" by 2050, which implies a reduction of GHG emissions by 90-95% (Norwegian Ministry of Climate and Environment, 2020). The implementation of a new hydrogen and CCUS plan are important to succeed with these ambitions.

Norway was the first Nordic country to formulate a strategy for both CCS and hydrogen. The CCS strategy goes back as far as 2014, while the Norwegian Hydrogen Strategy was launched in 2020 (Olje- og energidepartementet & Klima- og miljødepartementet, 2020) (The Norwegian Government). As a follow-up to the hydrogen strategy, the government published a road map on 11 June 2021 outlining the foreseen short-, medium- and long-term solutions for each offtake sector. The hydrogen strategy and road map also include CCS elements, given the Norwegian focus on various types of clean hydrogen, including green (renewable hydrogen), blue (low-carbon hydrogen) with CCS.

In the short term towards 2025, the government will facilitate that in collaboration with private actors a) five hydrogen hubs are established for maritime transport, with associated opportunities for land transport; b) one to two industrial projects with associated hydrogen production facilities are established, with the intention of demonstrating value chains with global potential; c) five to ten pilot projects are established for the development and demonstration of new and more cost-effective hydrogen solutions and technologies.

In the medium term, i.e. until 2030, the government foresees: a) a network of geographically dispersed and demand-based hydrogen hubs in line with the supply of vessels and vehicles; b) that hydrogen vessels are a competitive and safe alternative for shipping in Norwegian waters and short sea shipping areas; c) realisation of full-scale hydrogen projects in industry with significant export potential for Europe and the rest of

the world; d) that the use of hydrogen is a competitive alternative to fossil energy; e) that the Norwegian hydrogen business is linked to the development of a market for hydrogen in Europe through export of goods and services.

On CCS, the government's strategy aims at identifying measures to promote technology development and to reduce the cost of CCS. Norway has set a goal of realising a cost-effective solution for full-scale CO_2-management. The process industry will scale up CCS efforts, with the long-term goal of 5.5 Mt annual CO_2 eq reductions in 2050 (Olje- og energidepartementet & Klima- og miljødepartementet, 2020).

Since the government's hydrogen strategy was launched, the government has followed up on the strategy with NOK 100 million in the state budget for 2021 and a further NOK 100 million in the revised budget for 2021. The funds are intended for established schemes and existing collaborations and will be used to support technology and market development for hydrogen through, among other things, the establishment of the necessary infrastructure.

5.1.2 Existing policies and measures with the most significant impact on the different technologies

Research, innovation and end-to-end pilot and demonstration projects
Norway has in the last decade invested heavily in research environments in technology areas related to hydrogen through the Research Council of Norway. Two of the eight technology centres, MoZEES (zero-emission transport solutions) and NCCS (CO_2 management technologies) have hydrogen activities but are only part of the hydrogen value chain (Det Kongelige Olje- og Energidepartement, Meld. St. 36, 2021). In addition, it is suggested that a dedicated research centre for hydrogen and ammonia is established. Some funding is also intended to enable the business community to scale up production more quickly, safely and cost-effectively. The most central research and development programmes for hydrogen production and related activities are:

- ENERGIX: Focuses on technologies and solutions for the production, storage and use of hydrogen
- CLIMIT: Research in and development and demonstration of CCS-technologies for both power plants and industry, especially in relation to low-carbon hydrogen.
- Climate-Friendly Energy (FME) research centre: Brings together strong research environments and a large number of user partners from the business community and public administration within thematically prioritised technology areas. NOK 15 million have been set aside for an FME scheme within hydrogen and ammonia.

- Green Platform scheme: Gives companies and research institutes with support for research and innovation-driven projects for green growth. In the revised national budget 2021, the government proposes to strengthen the green platform with additional NOK 100 million. NOK 1 billion have already been set aside for the Green Platform (Meld. St. 36 (2020–2021) (regjeringen.no).

- The environmental technology scheme (under Innovation Norway): Aimed at developing, piloting and demonstrating new technologies for innovative products and processes that solve an environmental problem. It is particularly aimed at large projects and large companies (Det Kongelige Olje- og Energidepartement, Meld. St. 36, 2021).

- Zero Emission Fund: Supports hydrogen solutions in commercial vehicles and vessels.

In addition to these funding activities, Norway is part of IPCEI, and 5 projects have been nominated to be included in the Norwegian IPCEI effort (pending evaluation by the EU) (Det Kongelige Olje- og Energidepartement, Meld. St. 36, 2021).

Recognising that the funding landscape can be bewildering, the government has created the HEILO collaboration which aims at improving collaboration and consistence between actors and activities in the area. Moreover, the PILOT-E coordinates the available financing offers through challenge-oriented announcements and thus reduces risk for the actors by providing greater financing predictability throughout the development process (Det Kongelige Olje- og Energidepartement, Meld. St. 36, 2021).

In order to demonstrate hydrogen production and offtake capabilities, the Norwegian strategy also includes an increase in the number of pilot and demonstration projects for the full value chain of PtX and the establishment of a full-scale CO_2 management plant (Olje- og energidepartementet & Klima- og miljødepartementet, 2020). For example, the Norwegian government has supported the Topeka project for the construction of two ro-ro vessels servicing the short sea segment, with a total funding of NOK 219 million. The vessels will, among other tasks, move goods between offshore supply bases along the Norwegian west coast and transport hydrogen to filling stations where local ferries and other vessels as well as land transport will have hydrogen as a ready-to-use fuel (Wilhelmsen, 2020).

Norway has launched several pilot projects on CSS and now ventures into full-scale solutions. The most known pilot project is the Technology Centre Mongstad, the world's largest facility for development and testing of carbon capture technologies.[5] As mentioned in section 2.5, full-scale carbon capture solutions are planned as part of the Longship project, in which captured CO_2 from the Norcem Cement plant and Fortum Oslo Varme, with a combined capacity of about 800,000 tonnes of CO_2 per year, is sent through a pipeline to a storage site on the continental shelf off the western coast of Norway (CCS Norway, 2020). Recently, the government has approved the storage-part of the Longship project, Northern Lights and covers around two-thirds of CAPEX and OPEX costs (Norwegian Government, 2021).

Finally, Norway is a member in several international hydrogen-related groups, for example in CEMs Hydrogen Initiative and IPHE. Norway is also an active partner in, and secretariat of, the international funding initiative Accelerating CCS Technologies (ACT) and the Norwegian Ministry of Petroleum and Energy recently became member of the European Clean Hydrogen Alliance (Det Kongelige Olje- og Energidepartement, Meld. St. 36, 2021).

Market framework conditions

The Norwegian Hydrogen Strategy focuses on the development of infrastructure for production and consumption of hydrogen with low emissions, especially for heavy road and maritime transportation. Regarding the latter, Norway has for a long time had a focus on promoting zero- and low-emission high-speed ferries, which also include hydrogen solutions. The strategy, complemented with financial incentives, will build hydrogen and ammonia charging infrastructure and develop a public tool to provide an overview of infrastructure for alternative fuels for road and sea transport. Furthermore, Norway wants to map all ferry connections, high-speed ferry connections, and other maritime scheduled traffic to find out which zero-emission technologies may be suitable (Olje- og energidepartementet & Klima- og miljødepartementet, 2020).

Further, Norway intends to contribute to developing regulations and standards nationally and internationally for the use of hydrogen and hydrogen-based solutions within new areas of use, and in step with technology and market developments. In addition, for regulations, investments in new competencies in the Norwegian authorities will be prioritised, including the Maritime Directorate and the Norwegian Coastal Administration.

5 The centre has access to flue gas from the natural gas combined heat and power plant as well as from the refinery cracker which provides a unique opportunity to i nvestigate capture technologies relevant for coal and gas fuel power plants along with other industrial applications.

> Norway was the first country in the world to implement a financial incentive for CCS in the shape of an offshore carbon tax, enacted in 1991, that led to the development of the early Sleipner and Snøhvit CCS projects.

Norway has taken some financial measures to stimulate both demand and supply of green fuel. On the supply side, power supplied for use in electrolysis is currently exempt from the electricity tax. On the demand side, hydrogen cars will – similarly to electric vehicles - be subject to low tax and a range of utilisation benefits until 2025, as battery electric cars have been for some time. The benefits include exemption from road tolls and free parking in city centres, and sometimes even surpass those for electric vehicles. Finally, to increase the demand for low- and zero-emission solutions within transport, the hydrogen strategy includes actions towards climate- and environment-friendly public procurement (Olje- og energidepartementet & Klima- og miljødepartementet, 2020).

Norway was the first country in the world to implement a financial incentive for CCS in the shape of an offshore carbon tax, enacted in 1991, that led to the development of the early Sleipner and Snøhvit CCS projects (Jeffrey P. Price, Bluewave Resources & McLean, 2014). Further pricing of emissions through taxes and a quota system will help to promote low-emission solutions. A tighter quota market, together with the government's announced escalation of the CO_2 tax, will make emission-intensive solutions more expensive, and low-emission solutions such as hydrogen more competitive. In the government's climate plan for 2021-2030, it was announced that the government will increase the tax on greenhouse gas emissions, which makes it more profitable to choose climate-friendly solutions. The CO_2 tax, which is currently around NOK 590/ton, will increase to NOK 2,000 by 2030.

5.1.3 Conditions for implementation

Enablers

Norway has a large oil and gas industry with an export value of NOK 333 billion in 2020, which amounted to 42% of the total value of Norwegian exports of goods (Olje- og energidepartementet, 2021). The shift in focus towards greener fuels, in particular by the EU, means that the oil and gas

industry need to be reinvented. A special driver for Norway is, therefore, to use natural gas from the North Sea and transform it into low-carbon hydrogen. Indeed, the EU expects to import 40 GW of clean (renewable or low-carbon) hydrogen in 2030 (European Commission, 2020).
While there are no immediate plans in the strategy for converting the Norwegian export gas grid to a hydrogen grid, the focus on low-carbon hydrogen production with global potential means that there are future opportunities.

Norwegian hydro-power plants can deliver green, reliable and flexible power at low cost. The state-owned company Equinor is planning the world's first floating wind farm of 88 MW, Hywind Tampen, to power Snorre and Gullfaks offshore oil and gas field operations in the Norwegian North Sea (Equinor, the world's first renewable power for offshore oil and gas).

Norway has a tradition for the proactive implementation of new technologies (i.e. electric passenger cars, electric ferries) which means that consumers generally have a high social readiness level (SRL) towards new technologies.[6]

Critical barriers
In Norway, there has been safety concerns regarding hydrogen production and utilisation and carbon storage facilities, following an explosion of a hydrogen filling station in Sandvika near Oslo in 2019. The hydrogen strategy also addresses issues of the safe use and production of hydrogen.

While the export of low-carbon hydrogen could be a desirable option for the Norwegian energy sector, the long-term priority for the EU is to develop renewable hydrogen, produced using mainly wind and solar energy, as this is compatible with the EU's long-term climate neutrality and zero pollution goal (European Commission, 2020).[7]

Standards and regulations need to be established before the medium-term export of low-carbon hydrogen can take place. For instance, gas quality standards need to be updated, since the Member States currently accept different levels of blending. Moreover, the reinforcement of policy

6 SRL is a measurement system used to assess the level of societal adaption of an innovation (whether social or technical), technology or product to be integrated into society, where TRL 1 is the lowest and TRL 9 is the highest level (Innovation Fund Denmark).

7 Fossil-based hydrogen with carbon capture is a subset of fossil-based hydrogen. Here, greenhouse gases emitted as part of the hydrogen production process are captured. The greenhouse gas emissions of the production of fossil-based hydrogen with carbon capture or pyrolysis are lower than those of fossil-fuel-based hydrogen, but the variable effectiveness of greenhouse gas capture (maximum 90%) needs to be taken into account.

instruments may be needed to secure cross-border coordination and system interoperability for an unhindered flow of gas across the Member States (European Commission, 2020). As it looks, the revised regulation for Trans-European Energy Networks (TEN-E) will support hydrogen and low-carbon gas projects in the efforts towards a future hydrogen network. It will also continue to support infrastructure for the transport of CO_2 for storage purposes (European Commission, 2020).

5.2 Finland

5.2.1 Political goals for the development of hydrogen, electrofuels, bio-CCUS and CCUS

Finland aims at being the world's first fossil-free welfare society. The current Climate Change Act (609/2015) sets the national long-term GHG emission reduction target at least -80% from 1990 levels by 2050. The long-term target is being reassessed as part of the Climate Act amendment. Furthermore, Finland aims at achieving carbon neutrality in 2035. Carbon neutrality will partly be achieved by strengthening carbon sinks and stocks, including CSS, in the short and long term (Finnish Government, u.d.). The carbon neutrality target will be assessed in 2025, including the potential role of international offsets (Ministry of the Environment, 2021).

There is no specific strategy for hydrogen, electrofuels or CCUS yet. Nevertheless, the Finnish Energy and Climate Roadmap 2050 from 2014 is clear that if CCS is not commercialised, the 80% reduction of emissions cannot be reached in practice (Ministry of Employment and Economy, 2014). 79% of industrial emissions are thought to be CO_2 that could be captured with CCS, and this reduction is impossible if CCS is not commercialised. There are plenty of emission sources that are relevant for biogenic CCS and therefore, this is preferred over fossil CCS. However, both are considered. The road map from 2014 only briefly mentions hydrogen.

A revised National Energy and Climate Roadmap is planned in the fall of 2021, in which hydrogen and electrofuels are expected to play a big part in the industrial (especially in steel production) and transport sectors, (Ministry of Economic Affairs and Employment, 2021).[8] The road map already states that Finland will increase the share of renewable fuels in all transport fuels consumed in Finland to 30% by 2030, which would include hydrogen and electrofuels (Ministry of Economic Affairs and Employment, 2019).

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8 Concrete plans have been included in the National Energy and Climate Strategy, the Medium-term Climate Change Policy Plan (projections foresee a limited number of fuel-cell cars) and in Finland's plan for deployment of alternative fuels infrastructure (according to Directive 2014/94/EU) (EU Commission, 2020).

In preparation for the revised national road map, a process has taken place by which 13 sectors in Finland have developed sector-specific road maps in coordinated cooperation to achieve a better understanding of the scale, costs, and conditions of the required actions towards a carbon-neutral Finland in 2035 (Ministry of Economic Affairs and Employment, 2021). The 13 road maps repeatedly mention investments in new technological solutions related to alternative power carriers and CCUS.

5.2.2 Existing policies and measures with the most significant impact on the different technologies

Research, innovation and end-to-end pilot and demonstration projects
The government has established a Climate Fund in the budgets for 2021-24, based on the State Business Development Company Vake Oy. The fund has been capitalised with the equivalent of DKK 2.2 billion in 2020 and will annually receive an additional sum matching Nesté Oil refinery's dividends (DKK 4.6 billion in 2020) I (The Finnish State Development Company, 2020) (Neste, 2020). The purpose of the fund is, among others, to encourage green research and innovation activities.

There is currently a couple of interesting demonstration projects carried out by the private sector in Finland. For instance, the steel company SSAB has announced to be fossil-free in 2026, using low-carbon or renewable hydrogen in production.[9] Moreover, SSAB is working on the development of a Hydrogen Valley (Both2nia) between Finland and Sweden. The project is set to start in 2025, although a specific plan and anticipated applications for public support have not yet been published. To cover Finnish clean hydrogen requirements, Nesté Oil refinery is currently working on projects for producing low-carbon hydrogen. However, since it is currently not possible to store CO_2 in Finland and Sweden, conversations are ongoing with the partners of the Norwegian Northern Lights project. This may result in the shipment of CO_2 to western Norway. Finally, companies within paper production are working to replace methane with hydrogen.

Some demonstration projects with heavy public funding are also being carried out. Finland aims at introducing short-distance ferries running on hydrogen with filling stations at each end of their route. The Finnish city of Kerava has announced that it will use around 20 fuel cell buses for public transport, and the electricity needed for hydrogen production will come from a new three-hectare solar park.

Finally, an ongoing research project on electrofuels funded jointly by Business Finland, VTT, and the participating company partners, has

9 SSAB plans to introduce clean hydrogen in its Swedish production before production in Finland.

a goal of establishing readiness for scaling up the technology being developed to a production scale level after the project. The project aims at a breakthrough for Finnish technology on the growing world market for synthetic fuels (Bioenergy International, 2021).

Market framework conditions

As part of the EU, the Finnish market for energy production and consumption is regulated by EU regulations, such as the ETS, the Renewable Energy Directive and the Fuel Quality Directive. Furthermore, the government is currently implementing a series of strict regulations to increase the competitiveness of green fuels. For instance, Finland has raised the target for renewables in the overall fuel consumption by the transport sector to 30% by 2030. Currently, petrol and diesel distributors are required to blend in up to 20% of biofuel and biogas (Nordic West Office, 2020). However, a recent revision of the regulation includes electrofuels from 2023, providing a more level playing field in the market (Ministry of Economic Affairs and Employment, 2019).

Finland was the first country in the world to implement a carbon tax, in 1990, while Norway, Sweden and Denmark (Jeffrey P. Price, Bluewave Resources & McLean, 2014).

5.2.3 Conditions for implementation

Enablers

Finland has fixed national targets related to energy self-sufficiency which includes a decision to ban the use of coal for energy production by 2029 (Finnish Government, 2019).

Various companies e.g. Fortum, Neste, and Gasum have already established a production along the clean hydrogen value chain (Business Finland, 2020).

There are possibilities for increasing the use of hydrogen in the refinery industry if more vegetable oil is used as feedstock for producing HVO (Business Finland, 2020).

The south of Finland already has a natural gas pipeline, including a connection to the Baltic countries, which could be used for carrying hydrogen considering the safety and physical boundaries.

Critical barriers

Like most of the Nordic countries, Finland has a significant challenge in the implementation of hydrogen and electrofuels due to the lack of functional infrastructure to transport the fuels (Laaksonen, Aho, Silvennoinen, & Kortela, 2020). There is currently no national plan to remedy this issue, although some actors in the "hydrogen valley" are attempting to create a self-sufficient ecosystem. Because of the large distances, filling stations and other infrastructure are also expensive to build.

Finnish geography poses a challenge – while most low-carbon hydrogen production would take place in the south (Neste refinery in Porvoo), industrial offtake would primarily occur in central or Eastern Finland.

Only about 40% of Finnish electricity is based on renewable energy, which hampers the development of power-based green fuels. However, Finland is currently working on phasing out coal and increasing the share of nuclear power in energy production which will provide an opportunity for production of clean hydrogen. Moreover, due to limitations in cross-border connectivity, electricity import is severely limited, and thus market-based prices for electricity in Finland have usually been higher than in for instance Sweden and Norway.

Another problem is immature technology and large knowledge gaps related to the characteristics of hydrogen use outside of the professional base in the industry (Business Finland, 2020).

To date, there are no naturally occurring sites in Finland that could be suitable for storing hydrogen (Nordic Council of Ministers, 2020).

5.3 Sweden

5.3.1 Political goals for the development of hydrogen, electrofuels, bio-CCUS and CCUS

The Swedish Parliament adopted a climate policy framework with a Climate Act for Sweden in 2017 with the long-term goal of having negative emissions after 2045 (Nordic Council of Ministers, 2020). The milestone targets are: By 2020, emissions are to be 40 per cent lower than in 1990; by 2030, emissions are to be 63 per cent lower than in 1990; by 2040, emissions are to be 75 per cent lower than in 1990 Furthermore, Sweden aims at reducing emissions from domestic transport, excluding aviation, by 70 per cent by 2030, relative to 2010 (The Ministry of Infrastructure, 2020).

To achieve the goal of being one of the first fossil-free nations in the world, Fossil Free Sweden, an organisation that brings together actors in the form of companies, municipalities, regions and organisations, was started at the initiative of the Swedish Government in 2015. Fossil Free Sweden produces political proposals that are presented to the Government and brings together actors to implement politically agreed measures. In 2018, the similar project Fossil-free Air Transport 2045 (Fossilfritt Flyg Sverige 2045) was founded by private actors SAS, Swedavia, and RISE. The shared goal of the project is to end the use of fossil fuels for all domestic flights in Sweden by 2030 and for all flights that take off from Swedish airports by 2045 (Fossil Free Aviation 2045, 2021).

The government's Climate Policy Action Plan from 2019 mentions the use of hydrogen in relation to the industrial sector but does not provide strategic direction for production (Regeringen, Prop. 2019/20:65, 2019). However, focus has been sharpened since 2019, and the Swedish government is therefore looking to develop a national hydrogen strategy in the fall of 2021. As an inspiration to the national hydrogen strategy, Fossil Free Sweden presented a hydrogen strategy in 2020, in which it is recommended that the government sets a goal of 3 GW installed electrolysis power by 2030 and at least 8 GW by 2045 (Fossil Free Sweden). Fossil Free Sweden also sees the potential of the use of hydrogen in other sectors than industry, such as agriculture and construction and real estate and transport (although biofuels are currently the focus for the transport sector through blending requirements).

The Climate Policy Action Plan also mentions CSS based on the combustion of biomass (bio-CSS), especially from heating, as a tool to reach the climate goals. Furthermore, the interest in CCS has increased in Sweden, especially after the Swedish Government Official Report SOU 2020:4 mentioned CCS as a tool in places where other measures are not possible. More specifically, Sweden has a large number of significant point emission sources of biogenic carbon dioxide from the pulp and paper industry and fossil carbon from cement industry that could be subject to CCS (SOU 2020:4, Vägen till en klimatpositiv framtid).

The Swedish Recovery and resilience plan under the NextGenerationEU does not specify national plans for Hydrogen, electrofuels or CCUS (Finansdepartementet, 2020).

5.3.2 Existing policies with the most significant impact on the different technologies

Research, innovation and end-to-end pilot and demonstration projects
There are several public funding options in Sweden. The cross-sectoral policy instruments, the Industry Leap and the Climate Leap, are cases in point. The Industry Leap is a long-term government programme that supports the development of technology and processes to reduce process-related greenhouse gas emissions from Swedish industry. The grant scheme is planned to run until 2040, and support can be given to research, preliminary trials, testing, pilot and demonstration projects, detailed planning studies and investments in measures to reduce emissions as well as to measures that seek to achieve negative emissions, e.g. bioenergy CCS (BECCS). The target group for this funding is industries with process-related emissions as well as universities and research institutions. In 2021, the government budgeted DKK 550 million for the programme (Ministry of the Environment, 2020). The Climate Leap, on the other hand, is aimed at cost-effective measures that lead

to fulfilling climate goals and is often given to smaller projects with more well-established technology. It has been particularly important for transforming the transport sector.

There are several private industrial initiatives in Sweden where the production and use of hydrogen is planned, some publicly funded:

> SSAB, LKAB and Vattenfall are working on developing technical solutions to significantly cut carbon emissions from the steel industry in the HYBRIT project. In 2018, they started building a pilot plant for fossil-free steel production with financial support from the Industry Leap. The main goal is to develop a complete solution for fossil-free steel by 2035 (Ministry of the Environment, 2020).[10]

> Stockholm Exergi is planning a bio-CCS plant at the biofuel-fired CHP plant in Värtan with the potential to capture 800,000 tonnes of carbon dioxide per year (Stockholm Exergi).

> H2 Green Steel is planning to build the first large-scale production site for fossil-free steel located in Boden-Luleå, Norrbotten. The plant will be a fully integrated, digitalised and automated greenfield steel plant. The planning includes all parts of the value chain, including automotive, commercial vehicle, white goods, furniture and industrial equipment (H2 Green Steel).

> Göteborg Energi, Nordion Energi, Preem, St1, Renova and Gothenburg Port Authority, the CinfraCap project aims at developing full-scale carbon capture and storage facilities at several refineries. This will produce a more comprehensive picture of the logistics chain required to transport captured carbon dioxide from industrial facilities in western Sweden – from liquefication and intermediate storage to loading ships and onward transport to the repository site (Gothenburg Port Authority, 2021). Discussions are currently taking place on storage via Northern Lights in Norway (CCS Institute, 2020). The aim is to transport 2 Mt CO_2 annually by pipelines for permanent storage in a reservoir 2,600 metres under the seabed on the continental shelf in the northern part of the North Sea, southwest of the Troll field and east of the Oseberg field (Northern Lights). The Swedish Energy Agency is helping draft a shipping agreement with Norway for captured CO_2 .

> Heidelberg Cement is currently building the world's first carbon neutral cement plant in Gotland Island planning to capture 1.8 million tonnes of CO_2 annually from 2030 onwards. The captured CO_2 will be

10 If successful, HYBRIT can reduce Sweden's CO_2 emissions by 10% and Finland's by 7% (Ministry of the Environment, 2020).

transported to a permanent storage site offshore several kilometres down in bedrock underground in oil and gas fields. The company aims at creating a new stream of revenue by selling captured carbon to other industries. Heidelberg Cement still needs to reach an agreement with the Swedish Government on financing the facility in Slite which is estimated to cost 325 million euros (Industry Europe, 2021).

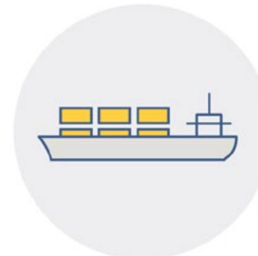
Sweden's policy instruments in the industry sector incentivise the use of renewable energy, improving efficiency and a transition in the basic process entirely.

Market framework conditions

As part of the EU, the Swedish markets for energy production and consumption is regulated by EU regulations, such as the ETS, the Renewable Energy Directive and the Fuel Quality Directive. Sweden seeks an energy transformation through market-based policies that focus on energy efficiency and renewable energy, notably with CO_2 taxation and obligations to reduce emissions, which helped drive decarbonisation in several sectors. Sweden also has energy taxes, a tax on air travel and a differentiated vehicle tax. The government is currently working on creating financial incentives for CCS in the shape of reversed auctioning or storage money (Energimyndigheten, 2021).

Sweden's policy instruments in the industry sector incentivise the use of renewable energy, improving efficiency and a transition in the basic process entirely. Much of Sweden's industry has signed up to the Fossil Free Sweden initiative (see section 4.2.3), and work on the initiative serves as an important driving force in the sector (Ministry of the Environment, 2020). The industry has certain energy and carbon tax reductions and exemptions, basically because most of the manufacturing industry is already covered by the EU ETS. The manufacturing industry that falls under the EU ETS pays 30 per cent of the general energy tax and is entirely exempt from carbon tax. The manufacturing industry not included in the EU ETS also pays 30 per cent of the energy tax on fuel used in the manufacturing process (Ministry of the Environment, 2020).

Both petrol and diesel fuels are subject to an energy and a carbon tax on fuel used for road vehicles, non-road mobile machinery and private vessels and aircrafts. All high-blend sustainable biofuels are exempt from energy tax and carbon tax, but electrofuels are not yet considered. An



emission reduction obligation on petrol and diesel also encourages the use of biofuels. Electrofuels are currently not included as an alternative in the reduction obligation, but the government has suggested their inclusion in the near future (Regeringen, Reduktionsplikt för bensin och diesel – kontrollstation 2019, 2019). To make renewable fuels available, legislation in Sweden requires large filling stations to offer at least one renewable fuel (Ministry of the Environment, 2020). Finally, a public analysis on phasing out fossil fuels puts considerable emphasis on the use of electrofuels and hydrogen in transportation (Regeringen, 2020) (SOU 2021:48, Sverige utan fossila drivmedel 2040).

Other financial initiatives have also been introduced in the transport sector. The government has allocated funding for an eco-bonus system to stimulate switching goods traffic from road to sea, and Sweden has introduced a tax on air travel with the aim of reducing the climate impact of aviation.[11] Vehicle-related measures include a bonus–malus-system for new light vehicles in which vehicles with low carbon dioxide emissions can qualify for a bonus on purchase and a carbon dioxide-based annual vehicle tax (Ministry of the Environment, 2020). There is also the possibility of a tax reduction on eco-friendly company cars (Ministry of the Environment, 2020).

Finally, a climate premium allow regional public transport authorities, municipalities and companies to apply for a premium on busses, heavy vehicles and work machines, applicable to electric vehicles, charging hybrid vehicles and fuel cell vehicles for public use (Ministry of the Environment, 2020) (Regeringen, 2020).

5.3.3 Conditions for implementation

Enablers

Sweden has successful experience and knowledge in implementing green technologies and a high share of renewable power. The Parliament agreed in 2016 that power should be 100% renewable by 2040 (International Renewable Energy Agency, 2020) (Regeringen, overenskommelse om den svenska energipolitiken, 2016).

Critical barriers

Sweden has limited experience in hydrogen production and the use of hydrogen outside of industry.

There are significant barriers to implementing CCUS in Sweden: legal barriers, including a complex permit process for building CCUS facilities, and lack of financial incentives. Plants that capture emissions of both bio

11 The tax is designed as a tax on commercial flights and is paid for passengers traveling from an airport in Sweden.

The Danish government has called for industry-wide roadmaps for both green fuels for transport (PtX, etc.) and CCUS through Innovation Fund Denmark as inspiration for the strategies.

and fossil origin are caught in a financial impasse, as support schemes and regulations usually focus on one or the other. In addition, there has been considerable political and public disapproval of carbon capture in Sweden, although this has improved recently, and the Swedish Energy Agency has received financial support to create a national centre for CCUS.

Ensuring the security of supply, sufficient distribution and transmission infrastructure and developing adequate market design encouraging flexibility in electricity offtake.

5.4 Denmark

5.4.1 Political goals for the development of hydrogen, electrofuels, bio-CCUS and CCUS

In 2020, the Danish Climate Act sets a target to reduce CO_2 emissions by 70% in 2030 relative to 1990 and to reach net-zero emissions by 2050 at the latest. The government's ambition is that all the necessary decisions for a road map towards the 2030 objective have been taken by 2025, and the government recently launched a roadmap with 24 specific initiatives to this end, which include PtX and CCUS (Danish government, 2021).

Denmark aims at developing cost-effective solutions for carbon capture and storage to reduce and eventually create negative CO_2 emissions. The technical reduction potential and goal for CCUS is estimated to amount to 4-9 million tonnes CO_2 e by 2030 with an overlap with the PtX potential. The technical reduction potential and goal for PtX is estimated to amount 0.5-3.5 million tonnes CO_2 e by 2030 and in the longer-term 1.5-7.5, also with an overlap with the CCUS potential (Danish Ministry of Climate, Energy & Utilities, 2020). Recently, the government's green recovery and resilience plan specifically mentioned carbon capture and storage as a key tool to reach the carbon reduction targets (technical reduction potential) of 4-9 Mt CO_2 by 2030 (Ministry of Finance, 2021).

Denmark intends to release its PtX and CCUS strategies by the end of 2021. Meanwhile, in the Climate Agreement for Energy and Industry of 20 June 2020, all parties in Parliament except one decided that capture and storage of CO_2 is important for the fulfilment of Denmark's climate policy goals. The parties agreed that, in the future, it should be possible to capture, transport and store CO_2 in Denmark as well as to transporting it across national borders provided that it is done in sound safety and environmental conditions (Energistyrelsen). The same parties have agreed on the first part of a CSS strategy on 30 June 2021, which consists of several initiatives grouped into three main tracks. The first must enable environmentally and safely sound storage in the Danish underground through a new authorisation regime and the removal of barriers in the short term, the second should make it possible to import and export CO_2, and the third must mature additional potential for storing CO_2 in Denmark in the longer term (Klima-, Energi- og Forsyningsministeriet). Furthermore, the sea plan, presently in public consultation, shows that the government wants to lay out most of the existing oil and gas area in the North Sea as well as a new area around Hanstholm, for CO_2 storage, a total area of 18,454 km².

The Danish government has called for industry-wide roadmaps for both green fuels for transport (PtX, etc.) and CCUS through Innovation Fund Denmark as inspiration for the strategies. There has been considerable interest from the industry in developing these, showcasing the generally strong attention to the topic.

5.4.2 Existing policies and measures with the most significant impact on the different technologies

Research, innovation and end-to-end pilot and demonstration projects

Several funding opportunities exist for hydrogen, electrofuels and CCUS projects. The Danish government created a Green Future Fund of DKK 25 billion in the 2020 state budget to contribute to, among others, the development and dissemination of new technologies. The fund will contribute to research into, among others, converting energy systems to renewable energy, storing and efficiently using energy as well as promoting global exports of green technologies, such as wind power and energy-efficiency improvements.

At the same time, the Climate Agreement on Energy and Industry from June 2020 includes a CCUS pool of DKK 16 billion in funding to support storage capacity in addition to capture and transport. In addition, a pool of DKK 200 million from the North Sea Agreement from December 2020 has been allocated to development and demonstration projects for CO_2 storage in the North Sea. The pool will promote storage in the North Sea underground as early as 2025 (Klima-, Energi- og Forsyningsministeriet). In addition, the Danish government has increased the level of green research funds to be invested in areas with a high impact on climate change. The government will maintain the level of the green research funds at least at the 2020 level, corresponding to DKK 2.3 billion in the coming years (Ministry of Higher Education and Science, 2020).

Through Innovation Fund Denmark (2021), the government has also set aside DKK 700 million in 2021 for investments in mission-driven green research and innovation partnerships (Innomission-partnerships) within four areas. CCUS and green fuels (including PtX) are two of these four areas. The research into PtX, green fuels and hydrogen will build on a considerable Danish research tradition in hydrogen and electrolysis, in particular, to tap into a large potential for a commercial position of strength within PtX (Danish Ministry of Climate, Energy & Utilities, 2020). The aim is thus twofold: to reduce domestic emissions and to develop new technology areas with export potential, as with wind energy.

Another important tool is the public grant scheme Energy Technology Development and Demonstration Programme (EUDP), which supports new technology in the energy sector which can help achieve Denmark's energy and climate goals – with a specific focus on electrofuels and CCUS. in 2021, the EUDP pool is DKK 543 million.

Several full-scale private projects within hydrogen and electrofuels in Denmark receive public funding:

- Green fuels for Denmark – A joint project by Ørsted, Copenhagen airports, DSV, DFDS, SAS, and A.P. Møller-Mærsk aiming at producing 1.3 GW of green hydrogen in Copenhagen by 2030, is supported by the Capital Region of Denmark and the City of Copenhagen in line with the municipality's ambitious policy for reducing CO_2 emissions. The project has also been qualified for the IPCEI programme (Plechinger, 2021).

- H2RES – A joint project by Ørsted, Everfuel, Nel, Green Hydrogen, DSV and Energinet to install 2MW annual electrolysis capacity in 2022 received DKK 34.6 million in government funding, through the EUDP.

There are no full-scale CCS projects in Denmark yet, but demonstration and pilot projects are under way at the different stages of the CCS chain – both for capturing and for storage. Several of these projects receive public funding:

- A public-private CCUS lighthouse project in the process industry, centred at the Aalborg Portland cement factory, is planned to test technology and develop competencies (Danish Ministry of Climate, Energy & Utilities, 2020).

- Amager Resource Center (ARC) installed a small pilot plant in May 2021 and is planning to build a full-scale capture facility for up to 450,000 tonnes of CO_2 annually from 2025. The Danish Research- and Demonstration Programme (EUDP) allocated DKK 30.12 million to the project.

- The Greensand project, owned by Ineos, Wintershall Dea, Maersk Drilling and GEUS, is working for safe and long-term storage of 0.5-1 million tonnes of CO_2 per year. In 2020, EUDP allocated DKK 9.61 million to the project (Energistyrelsen).

- Other players such as Aalborg Portland (capture) Dan-Unity (transport) and INEOS, Wintershall Dea, Maersk Drilling, the C4 cluster[12] (capture) and GEUS (storage) are also working on capture and storage projects (Klima-, Energi- og Forsyningsministeriet).

Market framework conditions

As part of the EU, the Danish market for energy production and consumption is regulated by EU regulations, such as the ETS, the Renewable Energy Directive and the Fuel Quality Directive.

In the Green Deal for Transport from December 2020, the government aims to increase the number of low-emission vehicles and stop the sale of fossil-based vehicles by 2030 (Ministry of Finance, 2020). Furthermore, registration fees will be redesigned to reflect the value of the car and its CO_2 emissions, and registration fees for zero-emission vehicles will be 40% of the regular fees in 2021-2025, slowly increasing to 80% in 2030. It is also agreed to have a technology-neutral CO_2 displacement demand of 7%, which slightly exceeds the FQD. Denmark will also step out of the non-mandatory Eurovignette agreement on road tolls to formulate a more CO_2-focused road toll for heavy trucks.[13] The government, moreover, made a political agreement in 2020 on legal requirements for wood biomass to provide greater assurance that the used biomass is as sustainable and climate-friendly as possible (Klima-, Energi- og Forsyningsministeriet, 2020).

Most of the political parties in Parliament reached an agreement in 2020 on a tax reform for industry (Ministry of Finance, 2020). In addition, in late 2021, an expert group will submit a report which clarifies a future

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12 The largest utility companies in the metropolitan Copenhagen work together to capture 3 M tons CO_2 a year. The companies behind the C4 consortium project are ARC, Argo, BIOFOS, Copenhagen Malmö Port (CMP), CTR, HOFOR, Vestforbrænding, VEKS and Ørsted.

13 The Eurovignette directive sets common rules on distance-related tolls and time-based user charges (vignettes) for heavy goods vehicles for the use of certain infrastructure. These rules stipulate that the cost of constructing, operating and developing infrastructure can be recovered through tolls and vignettes on road users.

CO_2 tax that moves in the direction of higher and more uniform taxation of CO_2 emissions, which is expected to boost demand for renewable fuels.

Danish electricity taxes are among the highest in Europe, which poses a challenge for the industry. Therefore, Green Lab Skive and Brande Brint (including Siemens Gamesa hydrogen project in Brande) have been offered a waiver from the Danish Electricity Supply Act, implying an exemption from taxes on renewable electricity (FuellCellsWork, 2021). The intention is that the area will function as a test zone and provide input for a possible reform of the act in relation to industry. Never before has an industry actor been exempt from the Electricity Supply Act and, therefore, the waiver is historical.

5.4.3 Conditions for implementation

Enablers

The Danish Parliament has agreed on cancelling the eighth licensing round and all future rounds for oil and gas extraction in the North Sea. It has also set a phase-out date for fossil fuel extraction by 2050. This is expected to speed up the development of green technologies, as companies that work with oil and gas extraction are expected to restructure their activities towards greener options.

The decision to invest in energy islands in Bornholm and the North Sea, with a direct mention of PtX production in policy texts, demonstrates Danish politicians' interests in the subject. However, the transmission connections and grid capacity issues need to be settled in time so the energy can be utilised for PtX production.

Danish universities such as DTU and Aalborg University have strong traditions for working with hydrogen and electrolysis and the industry sees a large commercial potential of PtX (Ministry of Finance, 2021).

Critical barriers

About 50% of biomass for Danish electricity and heat production is imported, and the amounts have increased steadily over the last 30 years (Danish Energy Agency, 2020). From a national perspective, there may in the future be competition for access to cheap, sustainable biomass, given that 1) the petrochemical industry will most probably need biogenic carbon for aviation fuels and 2) there will be a need for negative emissions via bio-CCS to achieve climate targets. An alternative to this would be carbon from direct air capture, but the technology is currently not expected to be available at a commercially competitive cost within a foreseeable timeframe. The uncertainty surrounding future access to sustainable biomass for production may reduce the incentive for the industry to set up production.

> The need for the transportation and storage of hydrogen through hydrogen infrastructure comprising pipes and storage facilities is the main market challenge.

Danish offtake readiness is low, especially for road vehicles, as consumers and freight operators have not been introduced to new technologies yet. For instance, although there is a large private Danish project planned for the production of renewable ammonia in Esbjerg, ammonia combustion technology for large ships is not yet ready, meaning that offtake in this sector is insecure. However, there are ongoing development projects on the topic. For instance, Nordic Energy Research, together with the national funding agencies, have funded three consortia exploring the use of ammonia/hydrogen as maritime fuels. Moreover, Maersk has recently placed an order for 8 new ships with a dual-fuel engine that can run on e-methanol, expected to be ready in 2023, and has agreed on a partnership with Reintegrate to establish a new Danish facility to produce the approximately 10,000 tonnes carbon neutral e-methanol. (Maersk, 2021).

The need for the transportation and storage of hydrogen through hydrogen infrastructure comprising pipes and storage facilities is the main market challenge in Denmark as well as in the other Nordic countries. Therefore, the Danish state-owned infrastructure owner Energinet participates in the European Hydrogen Backbone initiative for infrastructure owners (national and private) in 23 member states, which has presented an infrastructure map showing of new and retrofitted pipelines (Energinet, 2021).

5.5 Iceland

5.5.1 Political goals for the development of hydrogen, electrofuels, bio-CCUS and CCUS

Icelandic strategies reflect a clear willingness to phase out fossil fuels in the next three decades - and relatively fast in the case of road transport - and introduce extensive carbon capture activities for geothermal power plants and heavy industry. Hydrogen and other e-fuels, together with biogas, are seen as a viable option, especially as Iceland is in a unique position for large-scale production of fully renewable e-fuels.

Iceland launched a Climate Action Plan (*Aðgerðaáætlun í loftslagsmálum*) in 2018 and revised it in June 2020 (Ministry of the Environment and Natural Resources of Iceland, 2020). It focuses on two goals: exceeding the emission reduction commitments of the Paris Agreement for 2030 and reaching carbon neutrality for Iceland in 2040. The action plan consists of several Government measures, ranging from an increase in reforestation to ban on new registration of fossil fuel cars by 2030.

Part of the plan focuses on actions related to production and use of hydrogen and e-fuels, biomethane, carbon capture and incentives to stimulate the necessary transitions. Most of these actions are still being developed and thus only quantified to a small extent.

The Energy Strategy to 2050 (Sjálfbær orkuframtíð - Orkustefna til ársins 2050) from 2021, puts forward a vision for 2050. The vision entails (among others) production of renewable energy as the main tool to mitigate climate change, and it sees Iceland as the leader in sustainable energy production, transition, efficiency and efficient multi-use concepts, fossil fuel independency in 2050 and a complete phase-out of fossil fuels.

Iceland has had high ambitions within hydrogen production since the early 2000s. Several projects have already been initiated, for instance the European ECTOS project, using H2 fuel cell busses that were operating for some years in both Iceland and other countries. The national energy authority expects to issue a new energy forecast for Iceland in 2021 forecasting the shares of different renewable fuels. Icelandic New Energy (Nyorka) has published its own hydrogen strategy - A 2030 vision for H2 in Iceland - with focus on e-hydrogen in transport (Icelandic new energy, 2020). The national energy authority issued a new energy forecast for Iceland in 2021 forecasting the share of renewable fuels. Furthermore, a hydrogen and e-fuels road map is under development, and is planned to be completed in late 2021.

5.5.2 Existing policies and measures with the most impact on the different technologies

Multiple actions to achieve the vision are defined in the action plan (Ministry of Industry and Innovation of iceland, 2020), but rather qualitative than quantitative. A number of them focus on increased share of electricity and renewable fuels, especially hydrogen and other electrofuels, in transportation and maritime use, and their domestic production and potential large-scale export. The actions are also related to fuel enhancement and carbon capture R&D activities.

Existing incentives include the laws on renewable fuels for road transport from 2013, which came in force to implement the EU legal framework in accordance with the EEA agreement. The law allows double accounting of sustainable advanced fuels, such as hydrogen and other e-fuels. In 2012, a law was passed for exemption of VAT for vehicles operating on electricity and advanced renewable fuels, such as hydrogen and biogas.

In 2021, the CCS directive (2009/31) was adapted into Icelandic law. With the bill, the geological storage of CO_2 in Icelandic territory will be allowed, whether it is storage with conventional injection of supercritical CO_2 or injection for permanent mineral storage of CO_2 (such as the Carbfix method). With the legislation the administrative process for the injection of CO_2 in Iceland will be co-ordinated ensuring that permits, operations, reporting, verification and monitoring are in line with what is stipulated in the directive. In addition, it will ensure that parties under the EU ETS system will be able to deduct injected CO_2 under the new act in their ETS accounts, irrespective of which method is used, conventional storage or mineral storage.

Following the action plan, the Government of Iceland has allocated funding at an unprecedented level for hydrogen, electrofuels and CCUS. In the action plan, it is mentioned that the climate mitigation measures will get a substantial increase in funding with almost 7 billion Icelandic krónur in the period 2019-2023 (Ministry for the Environment and Natural Resources). Moreover, a general carbon tax, already in place, will gradually be increased. The action plan moreover launched a new fund to support amongst others; low-carbon technology; a phase-out for landfilling organic waste; and a phase-out programme for climate-warming chemicals. Further organised under the Ministry of Finance & Economic Affairs, the Icelandic Research Fund (RANNIS) administers several energy related funds in research and development of technologies. Furthermore, in 2021, the Icelandic companies Carbfix and ON Power received one of the highest amounts of approximately 600 million Icelandic krónur from the European Union's Innovation Fund for the Silfurberg project. The project is targeted to capture carbon dioxide from emissions of Hellisheidi geothermal plant (Think Geoenergy, 2021).

5.5.3 Conditions for implementation

Enablers

Iceland lies in an active volcanic zone that powers its geothermal systems and the glacial rivers contribute to Iceland's hydropower resources. Unlike most other renewable energy sources, geothermal power enables a stable production of electricity throughout the year. Furthermore, the country has tremendous wind power potential in which synergies between hydro power plants and wind farms can increase their overall efficiency and provide an efficient storage. Compared to the other Nordic countries, almost all Iceland's electricity and heating is provided by renewable energy. The position of Iceland makes it possible to produce renewable e-fuels at competitive power prices. The knowledge and experience gained from the last two decades, which also applies to large-scale CCS, will contribute to the development of technologies and implementation in Iceland.

Critical barriers
Some of the critical barriers and risks identified for the implementation of the technologies other Nordic countries are also relevant in Iceland, such as the need for standardisation and lacking hydrogen infrastructure. Storage and availability are still in development for a hydrogen infrastructure especially looking towards marine fuel use.

5.6 Cross-Nordic initiatives

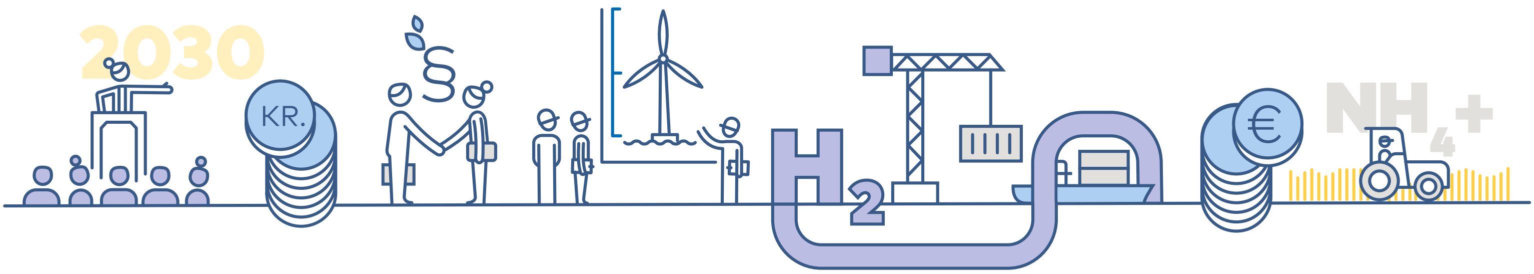
Several Nordic collaboration activities on policies and measures related to hydrogen, electrofuels and CCUS have already taken place:

- The Nordic CCS Competence Centre which was a top-level research initiative (TRI) existed from 2011 to 2015. Among others, the project resulted in a Nordic CCS road map.
- The Nordic capitals are supporting development of CCS technologies. The Carbon Neutral Cities Alliance (CNCA) (Amsterdam, Copenhagen, Helsinki, Stockholm and Oslo) has examined the latest CCS and CCU technologies to go carbon neutral (KlimaOslo, 2021).
- A Networking Group on CCUS within the Nordic Council (NGCCUS) was established in 2019 and consists of representatives from the Nordic and Baltic countries' ministries. The group meets twice a year.
- Nordic Energy Research ran a Nordic flagship project called Negative CO_2 which explored more effective and cost-efficient methods to run a bio-CCS facility.
- Nordic Hydrogen Partnership is an organisation for intensified and extended cooperation between Norsk Hydrogenforum in Norway, Vätgas Sverige in Sweden, Icelandic New Energy in Iceland, Brintbranchen in Denmark and VTT in Finland. The five partners use their expertise to boost the cross-sector implementation of hydrogen and fuel cell technologies in the Nordic countries, in close cooperation with a number of industry representatives.
- The full-scale CCS project Northern Lights, which is planned on the west coast of Norway, has potential as a large-scale cooperation between the Nordic countries, given the ongoing dialogue between CCS projects in Sweden and Finland (through Sweden). The Swedish Energy Agency is helping draft a shipping agreement with Norway for the captured CO_2 .

- A new organisation, Nordic eFuel Alliance, has been established to address legal and market barriers for e-fuels, by cooperating within the Nordic countries. The collaboration gathers key e-fuel producers as members: CRI (Island), Norsk eFuel (Norway), Liquid Wind (Sweden), St1 (Finland).
- STRING, a political member organisation with 11 Nordic members from the regional and municipal levels (Viken County, City of Oslo, City of Gothenburg, Västra Götalandsregionen, Region Halland, Region Skåne, City of Malmö, City of Copenhagen, Region Zealand, The Region of Southern Denmark, The Capital Region of Denmark, Land Schleswig-Holstein, The Free and Hanseatic City of Hamburg) is in the process of establishing a hydrogen corridor with refuelling stations for hydrogen heavy-duty vehicles from Hamburg to Oslo. The project aims at deploying a minimum of 12 hydrogen refuelling stations and a fleet of up to 570 hydrogen heavy-duty vehicles in the corridor.

SHORT CONCLUSION

This chapter has addressed the framework conditions for the Nordic countries in engaging further in the development of the technologies. In the next chapters, the Nordic synergy opportunities are identified.



Chapter 6

NORDIC STRENGTHS AND SYNERGIES

The Nordic region is well positioned to build on its strengths, including ambitious energy and climate policy goals, an abundance of renewable energy resources at a competitive low cost and potential for underground storage of hydrogen and carbon, a well-established R&D environment and technology know-how, several world-class companies with cross-Nordic ties eager to transition into new energy production.

From a value chain perspective, the access to natural resources and the geographical characteristics of the region provides a strong base. Combined with a supply side that has picked up significant pace and a demand side that is ambitious in goal setting, there is a good case for the harvesting of both individual and Nordic strengths and synergies by both public and private stakeholders.

Nordic cooperation across the hydrogen, electrofuel and CCUS value chains covering the production, storage, distribution and consumption segments building on the identified strengths could produce a greater combined effect for the Nordic region in an increasingly competitive European and global context.

6.1 High political readiness

As described in chapter 5, each of the Nordic countries has ambitious energy and climate policy goals and the Nordic countries are currently working towards developing or implementing strategies for hydrogen, electrofuels and CCUS as supplements to their climate strategies. Norway was, in 2020, the first country to publish a hydrogen strategy, and has since published a road map which, among others, specifies the goals for infrastructure development. Denmark and Sweden will release their hydrogen strategies by the end of 2021, and Finland and Iceland are working on updates or additions to their climate strategies, in which hydrogen and electrofuels are expected more prominent roles. Iceland aims to publish their road map for hydrogen and e-fuels this year (2021).

The use of CCS and CCU are increasingly becoming more acceptable and are now a possible emission reduction technology in all the Nordic countries. Norway presented its ambitious strategy as early as 2014, including for both biogenic and fossil CCS, and due to the Norwegian inclusion of low-carbon hydrogen, its hydrogen strategy also includes CCS elements. Denmark has also recently released the first part of its CCS strategy which at this point does not differentiate between biogenic and fossil CCS. Sweden has yet to set up a strategy for CCS, and the country has seen some scepticism towards the technology. Nevertheless, bio-CCS is recently considered a possibility in order to achieve the Swedish climate goals. Finland and Iceland have not stated specific national goals for CCS. However, Finland has been explicit that it cannot reach its climate goal without fossil and biogenic CCS, and CCS has been part of the Icelandic reduction effort for several years under the Carbfix project.

The political readiness indicated by climate targets and strategies can be considered a strength as it sets a clear direction for the industry, which in turn will find investments in production facilities to be less risky. In further recognition of the need to involve the industry, several Nordic countries have prepared road maps across sectors with close involvement from private actors to achieve a better understanding of the required

The Nordic region has a significant potential for renewable power which can be used to produce, consume and export hydrogen and electrofuels to continental Europe.

conditions to achieve carbon neutrality. In Denmark, this has been done through calls for mission-driven roadmaps by the Innovation Fund, while in Sweden, the government has created the hybrid organisation Fossil Free Sweden to advise on policy. The inclusive process by many Nordic countries ensures prudent policies that are conducive to developing the industry, on the one hand, and confirms involvement and understanding of policies by the industry, on the other hand. Multiple stakeholder fora already exist, also on a Nordic level. To understand the needs of the industry in a cross-Nordic perspective, such stakeholder involvement sessions should continue. Furthermore, for the fora to be successful, they should have a clear purpose and consider issues that are of particular relevance to the Nordic context. For example, prioritising the major technical and enabling challenges that exists across the Nordic region. They should also include different levels of stakeholders, including the ministerial, technical and commercial level.

6.2 Natural resources that are available and affordable

Renewable power

Renewable power is the key to the transition. The Nordic region has a significant potential for renewable power which can be used to produce, consume and export hydrogen and electrofuels to continental Europe. Although the Nordic countries vary in relation to their access to, and affordability of, green electricity, the countries generally have a high level of renewable power in the electricity mix compared to European standards. For example, Denmark has high shares of wind power, Norway and Sweden have a lot of hydropower and Iceland has geothermal power. The availability of renewable power means that the Nordic region has very low electricity prices for renewable energy. Electricity prices from renewable energy in the Nordic region could be as low as EUR 0.03–0.04 per kWh (Nordic Council of Ministers, 2018). The Nordic countries have access to low-cost renewable energy, the surplus of which can be used to produce hydrogen and decarbonise the Nordic industry and transport sector and for export to the rest of Europe (e.g. to Germany which is expected to be the largest consumer of hydrogen in Europe).

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There are variations in how much the countries seek to invest in making new power available for hydrogen and electrofuel production. In every country, wind power is expected to increase significantly. The Nordic countries have decided on ambitious plans for expanding the renewable energy production, which gives a clear indication of government commitment to the agenda. Indeed, the Nordic Energy Technology Perspectives scenarios foresee a five-fold increase in wind generation by 2050, which also displaces nuclear power. As of 2020, Nordic electricity generation is close to being decarbonised (87% carbon-free) and the Nord Pool area is well suited for integrating wind (Nordic Energy Research, 2020). Moreover, adjustments to hydropower plants and rescheduling of operations might improve access to hydropower significantly in Norway, Sweden and Finland. This could prove to be a significant potential in relation to the balancing of the overall power grid allowing for the integration of significant amounts of Nordic wind power.

The abundance of competitively priced renewable energy throughout the Nordic countries (existing and planned capacity) is the prerequisite for a sizable societal shift. In this respect, the Nordics benefit from the existing cooperation on power transmission – but could develop this even further ensuring an even more coherent power supply. To harvest potential synergies from the availability of renewable power in each country, the countries could investigate how planned power production in each country is expected to affect a joint Nordic power mix, and if any changes could be made to cross-border policies or power-transmission practises to improve conditions for Nordic companies.

Biomass

Besides renewable power, the Nordic countries have a considerable amount of available biomass for energy production, mainly due to the pulp and paper industries in Sweden and Finland, and the agricultural industry in Denmark and southern Sweden. Furthermore, Denmark and Sweden import large quantities of biogenic biomass, which is used for energy production.

Biomass can be used to produce bio oil and capture of CO_2 from biomass can be used to produce sustainable carbon-based chemicals and fuels for aviation, shipping and industry. Currently, for instance, biomass from burning waste product from the pulp and paper industry – which is considered carbon neutral – is emitted into the atmosphere. This carbon could be captured and either used for electrofuel production or it could be stored, resulting in negative emissions. Indeed, a market is under development for biogenic carbon capture offsetting, as companies like Microsoft are currently looking to buy negative emissions as a way of achieving company-set emission goals. At the same time, the carbon neutral industries are currently lacking the financial incentive and regulatory certainty to invest fully in carbon capture.

Moreover, studies show that in some countries, the energy demand from biogenic material for production of bio oils and electrofuels will exceed the supply of biomass each country.[14] Denmark, for instance, could be short of biomass for fuel production, especially as imports of biogenic material are expected to drop. This could pave the way for cross-Nordic collaboration of CCUS, where biomass-intensive areas in Sweden and Finland, for instance, collaborate with renewable-energy intensive areas in Denmark.

There are many questions relating the future availability of biomass and carbon, both in terms of the national biomass potential, the opportunity to continue import of biomass and the use of biogenic and fossil carbon sources for fuel production, which are currently unanswered. All of these are of high importance to the industry, and they all constitute potential risks to production. Thus, the Nordic countries could benefit from joining forces and consider coherent strategies for the future deployment of biomass. Furthermore, the Nordic countries could put joint pressure on international institutions such as the UN and EU to address whether numerous unanswered questions related to CCUS of biogenic (and fossil) sources.

Storage potential for hydrogen

The Nordic region has large-scale hydrogen storage capacity available in salt caverns. In fact, the storage potential of Denmark and Norway are ranked 4th and 5th, respectively, in Europe (Caglayan, D. et al.,

14 These studies assume that fossil point-source capture of carbon, for instance from cement production where decarbonisation is particularly hard, will not be an acceptable carbon source for electro-fuel production. Either way, access to point sources for fossil CO_2 will dwindle over the coming years with reduced emissions.

> The countries could investigate how different elements of the CCUS value chain in each country and transnationally is expected to affect the joint Nordic energy system and binding climate commitments.

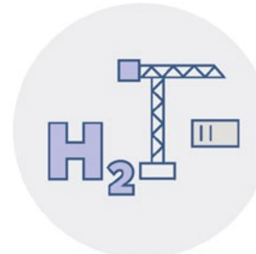
2020). Salt caverns offer a promising option for underground storage of hydrogen, owing to their low investment cost, high sealing potential and low cushion gas requirement (Caglayan, D. et al., 2019). While the Danish potential is located onshore or within 50 km of the shore, the Norwegian potential is located (over 50 km) offshore in the North Sea, implying that incorporating the caverns as part of energy system may be more challenging. Nevertheless, the potential for hydrogen storage in salt caverns is a clear strength for the Nordic region, and the countries could study further how to utilise these as part of the future energy system, for instance in relation to the Baltic pipe network.

Storage potential for CO_2

The Nordic region has unique access to offshore storage for CO_2. Norway is planning to and Denmark is looking into using part of the existing oil and gas infrastructure in the North Sea to develop offshore storage facilities, while Iceland is working on processes for binding the CO_2 in minerals as an onshore storage. Sweden and Finland have not identified any suitable storage formations and will probably rely on exporting the CO_2.

The geographic conditions in Norway and Denmark not only allow effective storage of national CO_2, but also open for storage of point-source CO_2 from the rest of the Nordics and Europe. This paves the way for an effective coherent Nordic solution for carbon storage. By linking Nordic storage facilities, the joined Nordic potential for storage could become even more effectively tapped. Nordic collaboration on carbon storage is already taking place through the Northern Lights project.

To harvest these potential synergies from the ongoing development of CCUS, the countries could investigate how different elements of the CCUS value chain in each country and transnationally is expected to affect the joint Nordic energy system and binding climate commitments, and if any changes could be made to cross-border policies or jurisdictions to improve conditions and support for Nordic stakeholders wishing to implement the technology. To further facilitate cross-border collaboration, both in the Nordic countries and elsewhere, the countries could work to increase the ratification level of the London protocol, which provides a legal basis for transport of CO_2 across national borders and consider the potential for a joint cross-Nordic agreement on transport of CO_2.



6.3 An easily deployed and competitive supply side

As driving down costs through research and innovation is a major concern for the development of the market, each country has established national funds to support research and innovation (Industriklivet in Sweden, Green Future Fund and Innovation Fund in Denmark, Energix and CLIMIT in Norway, Climate Fund in Finland and Orkusjóður in Iceland). This further supports the already strong research environment on related subjects in the Nordic universities and the strong partnerships across the private sector and universities. The Nordic region spends on average just under 3% of its GDP in the R&D area, significantly above the EU average (which is slightly above 2%) (Nordi Co-operation, 2020).

Considerable investments in projects are already taking place, generally reflecting each country's comparative advantage and expected offtake sectors. This has resulted in several publicly funded pilot and demonstration project in different fields, showing the natural diversity within the Nordic countries. Within CC technologies, examples are Carbfix in Iceland, Technology Centre Mongstad in Norway (the world largest test and development facility), and the Northern Lights storage facility. Large-scale renewable hydrogen projects are under development in Denmark (i.e. Green fuels for Denmark) and blue hydrogen projects in Sweden and Finland (HYBRIT and Hydrogen Valley). Nordic collaboration in the areas of hydrogen is already established.

In addition, several highly profiled projects, including significant participation by leading private sector stakeholders with the ability to implement projects in hydrogen, electrofuels and CCUS, have matured in the region the last few years. This allows hydrogen, electrofuel and CCUS projects to begin scaling up within the foreseeable future.

6.4 An ambitious demand side

Industry and heavy transport are thought to be the main offtakers for hydrogen and electrofuels in the future, closing the gap that a substantial societal electrification will leave in these sectors – where direct electrification is not feasible. Several industry leaders have already set ambitious zero emission goals.

The Nordic countries have a large number of potential consumers allowing synergies to arise by having offtake within a reasonable distance from the production plants. Sweden and Finland have relevant energy intensive industries where hydrogen can be used. Given the size of the Norwegian energy sector, offtake of Norwegian hydrogen is considered in a European perspective. With political incentives supporting the transformation towards hydrogen-fuelled transport, together the Nordic countries provide relevant offtake in size and nature that combines well with the production potential.

While hydrogen can be directly used in industry, renewable ammonia is expected to be used for fertiliser and e-fuels for marine transportation. As opposed to methanol, ammonia does not require a CO_2 source and can thus be produced at remote locations with access to cheap renewable power. Ammonia is a liquid which makes it easy to transport and is one of the most transported substance in the world.

E-fuels are expected to impact aviation and shipping in all countries, most likely in the shape of sustainable jet-fuel for aviation and either ammonia or methanol for international maritime transport. For short-distance ferries, batteries or hydrogen will be an option. There is not any significant difference between the Nordic countries in this regard.

All the Nordic countries have implemented CO_2 taxation, an effort that also works to increase demand for clean energy. These measures go beyond the EU ETS carbon pricing system, which the Nordic countries all participate in. CO_2 taxation is especially high in Sweden, almost half of that in Norway and Finland, and a quarter in Iceland and Denmark. In addition, Sweden and Finland has looked at additional measures to create financial incentive for offtake of CCS – such as reversed auctioning. Such measures were already taken in Norway in 1991 in the shape of an offshore carbon tax, which was a direct reason for development of the early Sleipner and Snøvit CSS projects. Several of the Nordic countries currently consider financial incentives for increasing demand for hydrogen, electrofuels and CCUS, such as increasing CO_2 taxation. To level the playing field and facilitate regional cooperation between companies, the countries could consider coordinating policies in the region.

6.5 Critical enablers for change

The possibility to distribute hydrogen and e-fuels easily is crucial for supporting a hydrogen-based economy. Across the Nordic countries, being able to interlink feedstock, power availability, production facilities and the users of hydrogen and e-fuels is important. Larger scale transmission is most efficiently done by ship or pipeline.

Norway, Sweden, Iceland and Finland all lack a national natural gas network that can be converted to a hydrogen network. Therefore,

hydrogen is likely to be used in heavy industries and produced close to the consumer. Sweden and Finland have ambitions of becoming part of the European backbone hydrogen network, with a pipeline along the coast of the Gulf of Bothnia. In Denmark, which has little heavy industry for which hydrogen is a relevant energy carrier, renewable hydrogen will likely either be used to produce e-fuels or exported through the potential European backbone hydrogen network. In Iceland renewable hydrogen could be used for production of e-fuels as a practical way to export energy from the country.

The Nordic port infrastructure is adequate for maritime based distribution, with facilities that can allow internationally sized transport. The existing pipeline infrastructure is also to some extent. Pipelines are the cheapest channel for distribution but require both planning and large investments in construction or refitting, thus needing substantially sized volumes to be economically viable. Pipeline infrastructure for natural gas which can be converted to carry hydrogen is already in place linking Sweden, Denmark and Germany, and a pipeline linking Poland, Denmark and Norway is planned to go into operation in 2022. It is clear, for instance, from the European Hydrogen Backbone initiative, that the countries have very different starting points for this. Sweden and Finland lack infrastructure for transporting hydrogen from the production centres to the main demand centres.

Nordic cooperation on the development of a coherent hydrogen distribution net for transportation has been going on for a significant number of years supporting and coordinating the spread of hydrogen fuelling stations. This is important in making road transport within and between the Nordic countries viable. Existing infrastructure and cooperation thus provide a strong basis for further harvesting the Nordic synergies in relation to distribution of hydrogen and e-fuels.

Finally, having the right skills is important for conducting a societal change. As both Norway and Denmark have halted fossil fuel extraction in the North Sea by 2050, which releases skilled labour with in-depth knowledge of large-scale offshore operations and other engineering skills for the hydrogen and carbon capture industry. An option for increasing the skills level of labour could be to develop cross-Nordic training programmes that focus specifically on the skills needed for building and working in hydrogen and electrofuel production and CCUS.

6.6 Summary of the strengths and synergies

The Nordic countries enjoy a high level of readiness in terms of ambitious energy and climate policy goals; available public and private investments; support for collaboration and R&D and competencies, including R&D and skilled labour with in-depth knowledge on the technology challenges.

The Nordics have a high availability of affordable natural resources and renewable power for the production of renewable hydrogen and storage of carbon. Sweden and Finland have steel and iron industries that can be decarbonised through new uses of low-carbon hydrogen. Similarly, Norway has one of the largest methanol industries in Europe. The organisation and finance for the supply side are well under way and seem ready for deployment. The industry and heavy transport sectors are ambitious and are already organising for maturing the demand.

On carbon storage, the Nordic countries already benefit from cross-Nordic collaboration, in a project where Finnish and Swedish companies ship captured CO_2 to storage points off the west coast of Norway. In addition, Denmark is looking into its North Sea storage potential. In fact, storage in the Nordic region could allow for long-term CO_2 storage, in quantities far exceeding the needs of the Nordic countries themselves. A synergy possibility would be to further support a Nordic network of carbon storage facilities. A first step could be to ensure that framework conditions for transportation are in place across the whole region, e.g. by considering a joint Nordic agreement on the transportation of CO_2 across borders in the region.

The Nordic countries also enjoy a comparative strength on the development of an appropriate solid infrastructure and distribution system. A major synergy opportunity would be to develop a Nordic port infrastructure for hydrogen distribution, which have direct access to major international markets via ocean freight. In addition, the availability of a pipeline infrastructure along the Baltic and North Seas can provide a direct link of the Nordic region to major European hydrogen users, where Germany could be a good export market of the Nordic region. The existing fuelling network with H2 stations covering the Nordic region can also be further developed close to major production and consumption hubs. Collaboration on regulatory measures that encourage the development of a coherent Nordic hydrogen transmission net is thus recommended to secure the distribution of large-scale renewable hydrogen to energy production facilities or various offtake sectors in the Nordics or as an export to the EU and UK (the network could be named "Nordic Hydrogen Backbone" to mimic the cross-European initiative).

Figure 6.1 gives an overview of the areas where the Nordic strengths can come into play as synergies.

Figure 6.1 Overview of potential Nordic strengths and synergies across the hydrogen and CCS value chains

Readiness

- The Nordic countries all have **ambitious energy and climate policy goals** spurring development in the industry within e-fuels and CCUS.
- A **high level of public and private investments**
- **Skilled labor** with knowledge of large-scale offshore operations and other engineering skills provides a comparative advantage for the hydrogen and carbon capture industry

Continued high support for collaboration and R&D can further reduce costs and make the Nordic region an attractive global export hub.

Production

- **High shares of renewable energy** allow the Nordic region to produce large amounts of clean e-fuels
- **Accessibility of biogenic sources of carbon** provides a long-term sustainability perspective for e-fuels
- **Low cost of renewables** in the Nordic region increases the competitiveness of Nordic hydrogen internationally

Storage

- Cross-Nordic collaboration in hydrogen storage in salt caverns allow large scale development of the Nordic hydrogen market.
- Resources in the Nordics allow for long time CO2 storage in quantities exceeding the needs of the Nordic countries.

Establishing a Nordic network of hydrogen and carbon storage facilities linked to production, distribution and consumption hubs would integrate hydrogen in the Nordic energy system

Distribution

- Nordic **port infrastructure** with direct access to major international markets via ocean freight can be used for global hydrogen distribution
- **Pipeline infrastructure** along the Baltic and North Seas can provide a direct link of the Nordic region to major European hydrogen users. Germany could be a good export market of the Nordic region.

Existing fueling network with hydrogen stations covering the Nordic region can be further developed close to major production and consumption hubs

Consumption

- Ambitious goalsetting by leading off-takers is influencing the strategic direction of a high number of stakeholders

Sweden and Finland have steel and iron industries that can be decarbonized through new uses of low-carbon hydrogen. Similarly, Norway has one of the largest methanol industries in Europe

CONCLUDING REMARKS AND WAY FORWARD

This study has shown that the Nordic countries are all developing renewable hydrogen, electrofuels and carbon capture technologies as climate-friendly solutions for their future energy systems. The Nordic governments have set ambitious emission reduction goals and are cooperating with private actors to develop the right framework to boost development.

The Nordic countries enjoy a high level of readiness in terms of ambitious energy and climate policy goals; available public and private investments; support for collaboration and R&D and competencies, including R&D and skilled labour with in-depth knowledge on the technology challenges. The inclusive process by many Nordic countries ensures prudent policies and should be further sought on a Nordic level to ensure a common Nordic understanding of the needs of the industry in a cross-Nordic perspective.

Building on the identification of Nordic strengths and synergies, the following recommendations and remarks on the national, Nordic and international level, respectively, can sum up the findings.

National level

- Study the potential for hydrogen storage. The countries could study the potential for hydrogen storage in salt caverns and further how to utilise these as part of the future energy system, for instance in relation to the Baltic pipe network.

- Investigate the energy and climate effects of the CCUS technology. To further harvest potential synergies from the ongoing development of CCUS in each country, the countries could investigate how different elements of the CCUS chain in each country and transnationally is expected to affect the joint Nordic energy system and binding climate commitments, and if any changes could be made to cross-border policies or jurisdictions to improve conditions and support for Nordic stakeholders wishing to implement the technology.

- Work for the ratification of the amendment of Art. 6 in the London Protocol. The Nordic countries are recommended to increase the ratification level of the London Protocol, which provides a legal basis for the transport of CO_2 across national borders. Although bilateral agreements between countries are now a viable option, ratification of the protocol has a considerable symbolic value.

- Investigate planned power production. To harvest potential synergies from the availability of renewable power in each country, the countries could investigate how planned power production in each country is expected to affect a joint Nordic power mix, and if any changes could be made to policies or power-transmission practices to improve the conditions for Nordic companies.

Nordic level

- Continue the stakeholder involvement. The countries should continue focus on Nordic stakeholder involvement sessions for developing a priority of technical and enabling challenges on a Nordic basis. The process should ensure inclusiveness and generate commitments from governments and the private sector for formulating a Nordic road map for enhancing organisation and synergies for the technology pathways.

- Collaborate on the potential for biomass. The Nordic countries could benefit from joining forces to get an overview of the national as well as collected Nordic potential for biomass and consider coherent strategies for the future deployment of biomass, including storage opportunities.

- Develop cross-Nordic training programmes. An option for increasing the skills level of labour could be to develop cross-Nordic training programmes that focus specifically on the skills needed for building and working in hydrogen and electrofuel production and CCUS.

- Develop a plan for the Nordic power mix. The Nordic countries could develop a plan for ensuring sufficient access to a renewable Nordic power mix to harvest synergies from the availability of different types of renewable power in each country. The plan should be based on an exploration of possibilities to improve policies or power-transmission practices to improve conditions for Nordic power generating companies

- Establish an ambitious goalsetting by leading offtakers. The Nordic region enjoys a strong collaboration on developing the future markets of renewable hydrogen and carbon storage opportunities. A synergy opportunity would be to establish an ambitious goalsetting by leading offtakers, which could influence the strategic direction of a high number of stakeholders. The Nordic governments are therefore encouraged to collaborate on the implementation of a scheme that ensures financial incentives for the production and offtake of renewable hydrogen, electrofuels and CCUS technologies, such as CO_2 pricing, taxation or reversed auctioning.

- Develop a Nordic model for hydrogen distribution. The Nordic countries also enjoy a comparative strength on the development of an appropriate solid infrastructure and distribution system. A major synergy opportunity would be to identify solutions to a Nordic cross-border infrastructure for hydrogen distribution that have direct access to major international markets.

- Support the development of a Nordic network for carbon capture and storage facilities. A first step could be to ensure that framework conditions for transportation are in place across the whole region for instance by considering a joint Nordic agreement on the transportation of CO_2 across borders in the region.

- Collaborate on regulatory measures. The Nordic countries are recommended to collaborate intensively on regulatory measures that encourage the development of a coherent Nordic hydrogen transmission net, a 'Nordic backbone', for the distribution of large-scale renewable hydrogen to energy production facilities or various offtake sectors in the Nordics, or as an export to the EU and UK.

International level

- Closer collaboration within the international institutions. The Nordic countries should collaborate in speeding up the processes in international institutions such as the UN and EU to agree on how to assess biogenic carbon as part of international carbon schemes, including financial support mechanisms.

- Closer collaboration in international processes. The Nordic countries are recommended to collaborate in international processes within the UN and EU on how to assess use of carbon from hard-to-decarbonise sectors and the various types of low-carbon hydrogen.

METHODOLOGY

The report is the result of a Nordic project, developed by COWI in dialogue with the Nordic Energy Research and a Nordic Steering Group. The project was developed between May 2021 and October 2021.

The design of the study has been based on an external analysis approach which can be categorised into three thematic teams, respectively, on Nordic policies and measures; on Technology pathways; and on market development and strengths. The mapping and the analyses were guided by preformulated research question that ensured that the teams worked unified and in line with the overall objectives.

The study has been developed as an iterative process, involving desk studies, interviews and dialogue with COWI's own experts as well as with experts and representatives of external organisations.

The sources of information for the desk studies included national studies from each of the Nordic countries, policy and legislation on PtX and CCUS technologies, including reports from the European Commission, Nordic Energy Research, TEMANord, IEA and more. All the references have been inserted in chapter 9.

The interviews and continued dialogue in the project team have been a key activity in order to map existing knowledge, opportunities and challenges as well as gather input on the technological pathways, Nordic strengths and synergies. The interviewees were selected based on the theme and cross-regional representation with a focus on all the Nordic countries. The interviews which were designed to confirm the findings were conducted.

Finally, a cross-Nordic workshops with the participation of eight leading industry organisations were held to verify the findings and identify Nordic strengths and opportunities for synergies. The themes on the workshop included the participants' views and Nordic perspectives on 1) available resources in the Nordic region, including power, biomass or other items such as storage opportunities for hydrogen and CO_2 ; 2) clean fuel technology pathways; 3) CCUS technology pathways, mapping specific Nordic technology strengths and potential synergies; and 4) discussing policies and measures for the industry, to get views on what regulation has the biggest impact on the industry, and if there are any regulatory barriers the Nordic countries could work to solve together. The workshop wrapped up by identifying a series of relevant recommendations for the development of Nordic collaboration.

Organisations that have contributed to interviews and workshops include:

- Ministry of Economic Affairs and Employment (TEM), Finland
- Brintbranchen
- Orkustofnun (the National Energy Authority)
- Carbfix
- Carbon Recycling International (CRI)
- SINTEF
- Norsk Hydrogenforum
- Energimyndigheten, Sweden
- VTT Technical Research Centre of Finland
- Vattenfall
- Equinor
- Northern Lights
- SSAB Raahe
- Port of Gothenburg
- Icelandic New Energy

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Definitions and abbreviations

AEC	Alkane electrolysis cell
BECCS	Bioenergy Carbon Capture and Storage
Biofuel	Biofuel is fuel produced from bio oil (see the definition of bio oil below)
Biogas	60% methane and 40% CO_2 based on production from biomass via anaerobic digestion
Bio oil	Bio oil is oil produced by pyrolysis, liquefaction or the HVO process. Bio oil also includes oil from the pyrolysis of plastic and tyres as it is assumed that these, with time, will become 100% biogenic.
Blue hydrogen	See fossil-based hydrogen
BNG	Biogas upgraded to natural gas quality by removing CO_2 and other impurities, leaving primarily CH4
CC	Carbon capture
CCU	Carbon capture and utilisation
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CH_2	Compressed hydrogen
CHP	Combined heat and power plant
Clean hydrogen	Renewable and low-carbon hydrogen
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CRI	Carbon Recycling International
DK	Denmark
DME	Dimethyl ether (C2H6O)
E-fuels	In this report, the term e-fuels refers to both biogenic as well as synthetic fuels produced by using renewable electricity.
ENDK	Energinet Denmark
EtOH	Ethanol (C_2H_5OH)
ETS	Emission trading system
EU	European Union
EC	Electrolysis cell
FAME	Fatty acid methyl ether (=biodiesel, C16-C81 esters)
FCEV	Fuel cell electric vehicle
Fossil-based hydrogen	Hydrogen produced through a variety of processes using fossil fuels as feedstock, mainly reforming of natural gas or gasification of coal
FQD	Fuel Qualitive Directive
Gasoline	Light hydrocarbons (C_4-C_{12}, typically C_7-C_{11}). Same as petrol.
GHG	Greenhouse gas
H_2	Hydrogen
HFO	Heavy fuel oil (typically C_{20}-C_{50})

HVO	Hydrotreated vegetable oil (typically C_{15}-C_{18})
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IPCEI	Important Project of Common European Interest
Jet-fuel	Highly branched hydrocarbon, C10-C13, mostly kerosene
LBG	Liquified biogas (mainly CH4) also referred to as Bio-LNG
LCA	Life-cycle assessment analysis
LH_2	Liquefied hydrogen
LOHC	Liquid organic hydrogen carriers (H2 carrier with the goal of making H2 transport cheaper)
Low-carbon hydrogen	Fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions when compared with the existing hydrogen production
LPG	Liquefied petroleum gas (primary C3-C4)
M85	Methanol gasoline blend with 85 wt% MeOH
MeOH	Methanol (CH_3OH)
MGO	Marine gasoil (typically $<C_{35}$)
Mt	Megaton (1,000,000,000 kg)
NG	Fossil natural gas (primarily CH4)
NH3	Ammonia
RE	Renewable energy
Renewable hydrogen	Hydrogen produced by the electrolysis of water (in an electrolyser, powered by electricity) and with electricity from renewable sources. Renewable hydrogen may also be produced by reforming biogas (instead of natural gas) or the biochemical conversion of biomass, if in compliance with the sustainability requirements
SMR	Steam methane reforming (eSMR=electrically heated steam methane reforming)
SOEC	Solid oxide electrolysis cell (high temperature with high efficiency)
TEN-E	The Trans-European Networks for Energy
TRL	Technology Readiness Level, a method for the estimation of the maturity of technologies
WtE	Waste-to-energy plants

About this publication

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