BalticSeaH2

Cross-border Hydrogen Valley around the Baltic Sea

D2.1 Baltic Sea region diagnosis

WP2 – Vision, social transformation and engagement

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Contents

Executive summary

This document presents country profile overviews for the nine countries participating in the BalticSeaH2 project: Finland, Estonia, Sweden, Norway, Denmark, Latvia, Lithuania, Poland and Germany. The purpose of the profiles is to provide an overview of each country's status, potential, and ambitions regarding the hydrogen economy. Additionally, the aim is to outline potential pathways for facilitating the transition to a hydrogen economy across relevant sectors while identifying readily available opportunities for hydrogen transition at the national level. A brief summary of the key results at the Baltic Sea region level is provided in Chapter 3. For the national-level results, please refer to the respective country profiles found in Appendices A-I.

This deliverable is part of WP2 – Vision, social transformation and engagement. VTT Technical Research Centre of Finland (VTT) is the responsible partner of this deliverable. Both qualitative and quantitative data for the build-up for the country profiles were collected from T2.1. partners (GG, FLX, EF, ECD, EVN, BIA, EHC, IWEN, GSTC, VEA, PHC) and through desktop research. The country profiles will serve as the foundation for the BalticSeaH2 Valleys vision work to be conducted in T2.2 "BalticSeaH2 Valleys' visions".

1. Introduction

This document provides country profile overviews for the nine countries participating in the BalticSeaH2 project: Finland, Estonia, Sweden, Norway, Denmark, Latvia, Lithuania, Poland, and Germany. A developed diagnosis process comprising of different data collection methods was utilized in the formulation of the country profiles to understand the current and future socio-technical-economic challenges associated with transitioning to a hydrogen economy in the Baltic Sea region. These profiles highlight key socio-technical-economic aspects crucial for assessing national opportunities for transitioning into a hydrogen economy, including national hydrogen strategies and targets, the current state of hydrogen production and consumption, potential for emission reduction, identification of key sectors with high hydrogen adoption potential, resource availability, infrastructure availability for hydrogen transmission and storage, clean hydrogen production plans and projects, potential geographical areas for hydrogen development, and socio-economic factors influencing the hydrogen transition at national level. The collected inputs will lay the foundation for the forthcoming work in T2.2 "BalticSeaH2 Valleys' visions" to realize long-term visions for the BalticSeaH2 Valleys.

2. Methods

The data collection, i.e. country diagnosis process, for this deliverable was facilitated through a country profile questionnaire developed jointly with T2.1. "Baltic Sea region (BSR) diagnosis & stakeholder analysis" and T7.2. "Baltic Sea region (BSR) hydrogen economy market and opportunity analysis" since the data collection for both tasks addressed similar topics. The questionnaire was circulated among the partners participating in both tasks. The questionnaire was structured into various themes, and the respondents were encouraged to consult other experts in the respective fields for each theme, ensuring comprehensive insights.

Furthermore, an Excel spreadsheet was created and shared among the partners to gather information on clean hydrogen production plans and current fossil-based hydrogen at national level. In addition, information on relevant stakeholders at national level that should be engaged in the project and in the vision work for the BalticSeaH2 Valleys to be conducted in T2.2. "BalticSeaH2 Valleys' visions", was collected. These stakeholders include various institutions such as national, regional and municipal authorities, financial stakeholders and investors, research and educational institutions, and non-governmental organizations. Utilizing the mapped stakeholders, a stakeholder analysis followed by a stakeholder engagement strategy (D.2.2) was formulated by EHC, outlining the best ways for interacting with each stakeholder group throughout the project.

After the partners completed the country profile questionnaires and Excel spreadsheets, VTT compiled the country profile overviews presented in this deliverable, by utilizing the data gathered from these questionnaires. This information was supplemented by desktop research via public online sources. Additionally, the country profiles incorporated data collected in T5.1. "Renewable energy for hydrogen production", particularly concerning renewable energy production potentials.

2.1. Ethics and Gender Dimension

Task 2.1. acknowledges that Ethics and Gender Dimension are an integral cornerstone of the work in BalticSeaH2, as the application of both contributes to the excellence and social relevance of the project. Hence upon conducting this deliverable, an Ethics & Gender Dimension lens was applied. In practice, gender-disaggregated data was gathered when it was available, and the deliverable also addresses a key component of an ethical hydrogen transition: Public awareness and social acceptance (see sub-sections *Public awareness and Social acceptance*).

However, it should be noted that little gender-disaggregated hydrogen-related information and data is available. The gendered-disaggregated information related to hydrogen is limited to findings in social acceptability studies, where women have been found to be more critical towards hydrogen technologies than men [1]. Meanwhile, hydrogen strategies, policies, and roadmaps in the Baltic Sea Region remain gender-blind, and also lack wider social justice considerations. This is even though research has demonstrated that both climate change and energy are gendered phenomena [2], [3], and that the political empowerment of women and their active involvement in decision-making and the labour market correlates with better environmental outcomes [4]. Recently, several international agencies and bodies, such as the International Renewable Energy Agency (IRENA) [5], European Institute for Gender Equality (EIGE) [6], and the United Nations [7] have also emphasized the need for gender-responsive climate action and gender-assessments on energy initiatives. Yet, these practices have not yet been widely mainstreamed into green hydrogen initiatives.

It is likely for the transitioning to clean hydrogen to involve critical gender-related questions related to workforce and talent availability, and gender-justice considerations when it comes to the siting of hydrogen infrastructure, energy pricing and poverty, and the phasing out of the fossil industry. Hence, it is advisable that the upcoming tasks and deliverables further integrate an ethical and gender-lens into the project activities.

3. Summary of key results

The resulting country profile overviews for the nine countries participating in the BalticSeaH2 project (Finland, Estonia, Sweden, Norway, Denmark, Latvia, Lithuania, Poland, and Germany) can be found in Appendices A-I. A brief summary of the key results at the Baltic Sea region level is provided below. For more detailed analyses of each subsection at the national level, please refer to the respective country profiles.

3.1. National hydrogen strategies and targets

Several countries have published government-issued national hydrogen strategies or roadmaps between the years 2020 and 2024 (Table 1). Finland does not have a national government-issued strategy related to hydrogen, but in 2023, a Finnish Government resolution on hydrogen was issued outlining targets and steps for developing the hydrogen economy within the country. In Sweden, although a proposal for a National Hydrogen Strategy was released in November 2021, it has not yet been officially adopted.

Table 1. Summary of government-issued national hydrogen strategies or roadmaps in the Baltic Sea region.

Country	Hydrogen Strategy/Roadmap
Finland	*Finnish Government resolution on hydrogen (2023)*
Estonia	Estonian Hydrogen Roadmap (2023)
Sweden	National Hydrogen Strategy of Sweden (2021)
Norway	The Norwegian Government's hydrogen strategy (2020)
Denmark	The Government's strategy for Power-to-X (2022)
Latvia	No strategy/roadmap
Lithuania	Lithuanian Hydrogen Development Roadmap for 2024-2050 (2024)
Poland	Polish Hydrogen Strategy (2021)
Germany	National Hydrogen Strategy (2020 and updated in 2023)

Quantified targets for electrolyzer capacity (GW) by 2030 have been set in national strategies and roadmaps for Sweden, Denmark, Lithuania, Poland, and Germany (Figure 1). In Finland, a key target outlined in the Finnish Government resolution is to produce 10% of the EU's emission-free hydrogen by 2030. Estonia's roadmap estimates the national hydrogen production potential to be between 2 and 40 kt/a by 2030, depending on market developments. While the Norwegian Government's hydrogen strategy lacks quantified production targets, it aims, for instance, to have 1-2 operational industrial projects with associated hydrogen production facilities by 2025.

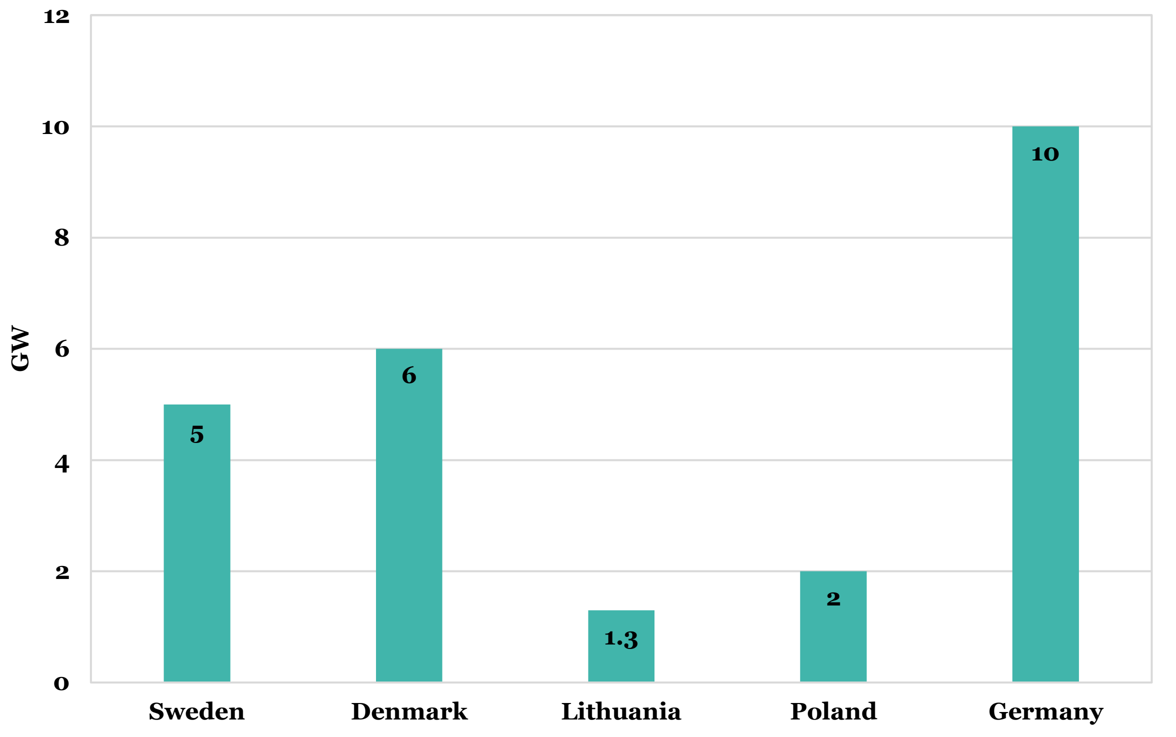

Figure 1. Quantified targets in national strategies or roadmaps for electrolyzer capacity (GW) by 2030.

3.2. Hydrogen state-of-play

The Baltic Sea region already has a hydrogen production capacity of **4.3 Mt/a**, with 90% of it being fossil-based reforming capacity (Figure 2). Germany (50%) and Poland (26%) have the largest hydrogen production capacities, while Estonia and Latvia, have very modest capacities, if not negligible.

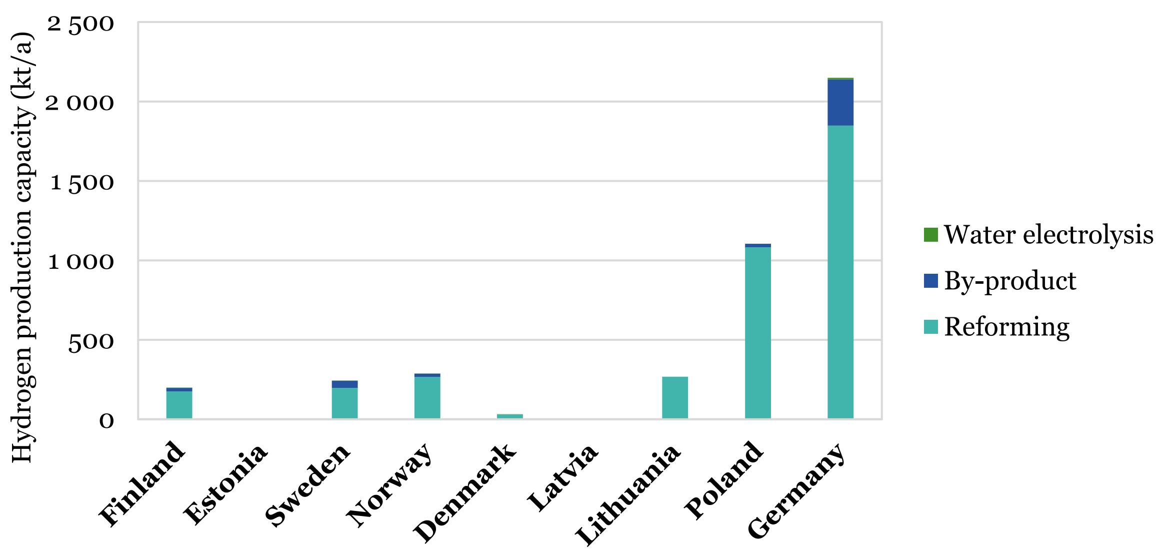

Figure 2. Hydrogen production capacitities in the Baltic Sea region [8].

The total hydrogen consumption in the Baltic Sea region was **3.2 Mt** in 2022. Germany (54%) and Poland (25%) were the largest hydrogen consumers. The refining industry (51%) was the main hydrogen consumption sector, followed by ammonia production (28%). The national-level hydrogen consumption in the Baltic Sea region varied from **0 to 1 750 kt/a** (Figure 3).

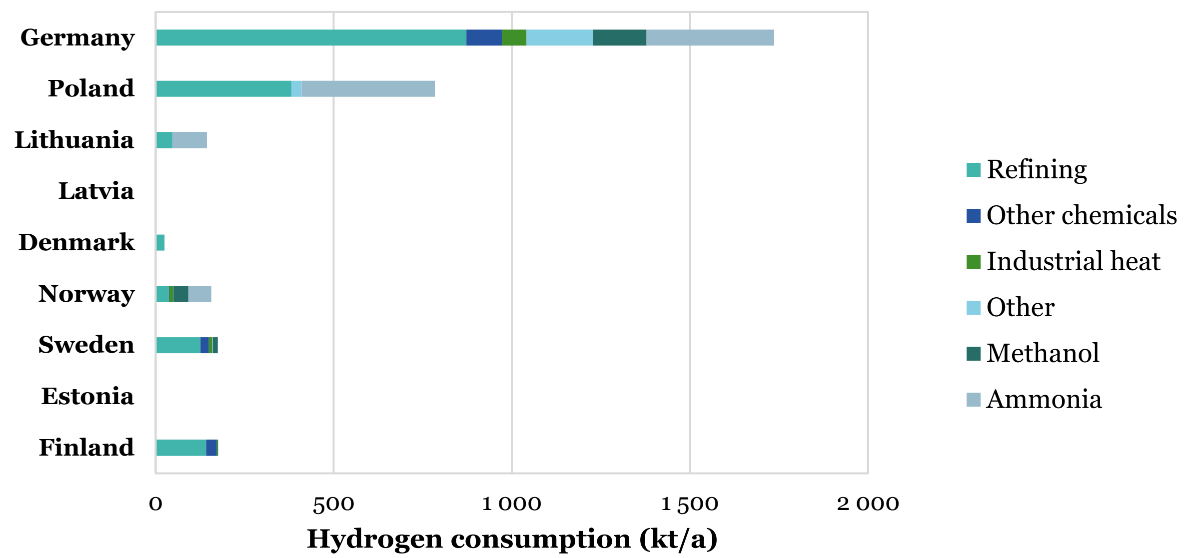

Figure 3. Hydrogen consumption volumes in the Baltic Sea region [9].

National emission reduction potential was estimated if all fossil-based hydrogen was replaced with a clean alternative (Figure 4). Steam methane reforming (SMR) was assumed as the hydrogen production technology with carbon intensity of 9 $kgCO_2/kgH_2$. Replacing current fossil-based hydrogen production would have the greatest impact on the emission reduction in Lithuania (11.9%), where the main hydrogen consumer is an ammonia production plant.

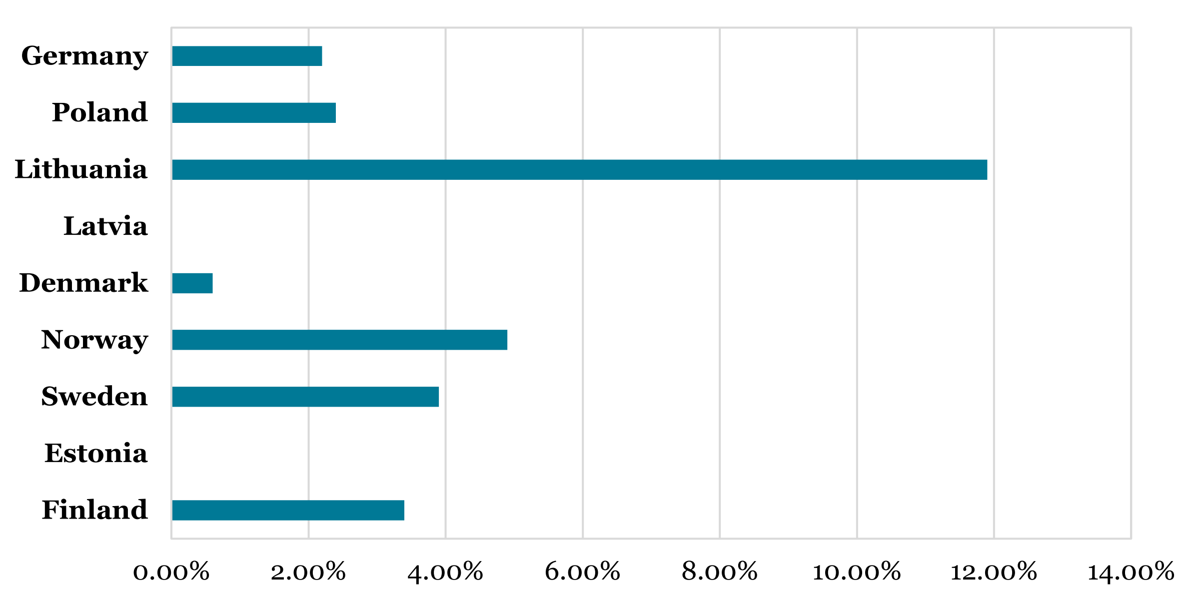

Figure 4. National CO_2 reduction potential through the direct replacement of fossil hydrogen production.

3.3. Hydrogen opportunities

3.3.1. Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonization exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. During the project, ammonia and methanol production plants as well as refineries were identified, as in these sectors, like-for-like substitution of fossil hydrogen by clean hydrogen is possible and decarbonising these sectors can be an important driver for clean hydrogen uptake in several countries. Locations of the identified plants can be seen in Figure 5. As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry. However, decarbonization of steel industry via hydrogen will require significant changes in the entire production process of primary steel. Primary steel production units in the Baltic Sea region, where decarbonisation via hydrogen could be a possible decarbonisation route, were also mapped (Figure 5).

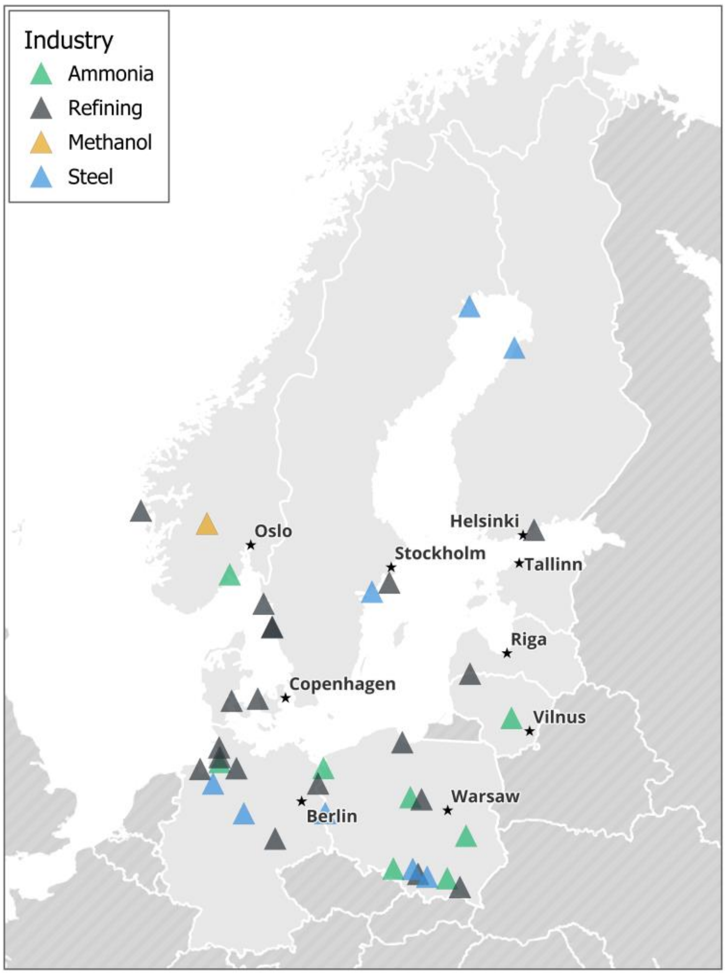

Figure 5. Examples of operational ammonia and methanol production facilities, refineries and primary steel production units in the Baltic Sea region. As for Germany, only the facilities in North-East Germany and the regions closest to the Baltic Sea were mapped.

3.3.2. Transport and logistics

As for other potential hydrogen use cases, hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. The countries in the Baltic Sea region have a large potential for hydrogen or hydrogen-based fuel use in road transport due to high shares of fossil fuel use in the sector (71-98%) as seen in Figure 6. An interesting use case for hydrogen in the Baltic Sea region is also hydrogen use in the rail transportation, especially in the countries where the share of fossil fuel use in rail transport is high, namely Estonia (92%), Lithuania (90%) and Latvia (78%).

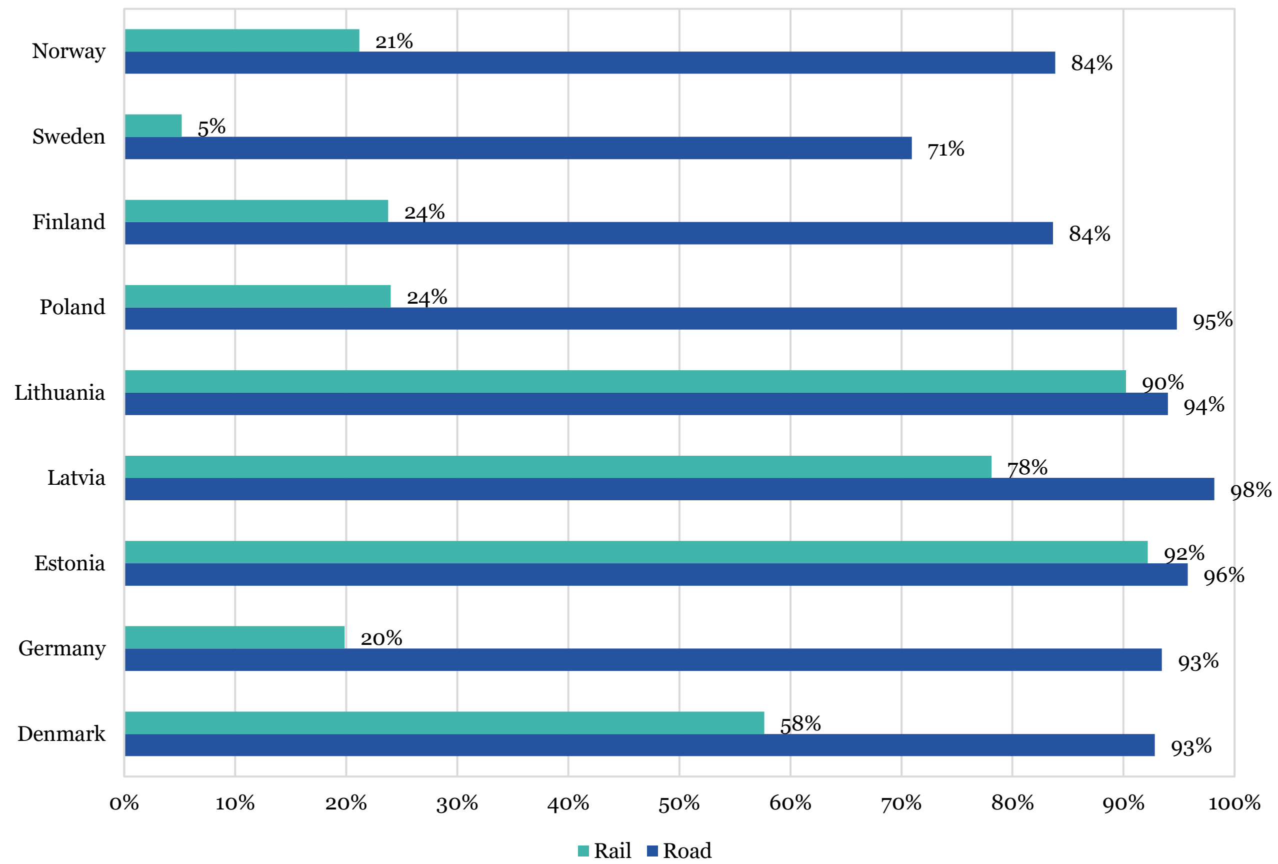

Figure 6. Share of fossil fuels in the energy demand of road and rail transport [10].

Maritime sector is also a key area with future potential for hydrogen-based fuels such as ammonia and methanol. Maritime sector as an important driver for hydrogen economy is highlighted especially in Norway, which also has the highest energy consumption in domestic navigation among the analysed countries (Figure 7). In addition to substituting fossil-fuels in the energy mix of the maritime industry, maritime sector is also interesting from hydrogen perspective, as the ports have the potential to become hydrogen hubs due to several reasons. Ports can provide fuel for ferries and bunkering operations and as ports can enable exports for produced hydrogen-based fuels and chemicals. Furthermore, hydrogen can be used to power vehicles and equipment for transport and other uses (e.g. forklifts, cranes, loaders) in the port areas.

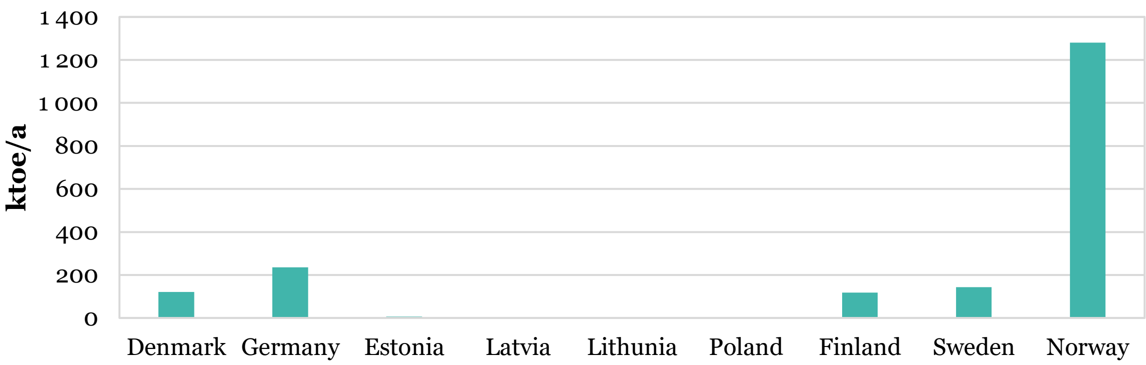

Figure 7. Energy demand in domestic navigation (ktoe/a) [10].

3.3.3. Hydrogen refueling infrastructure

As for the hydrogen refueling infrastructure, the analysed countries are at various stages of development. Operational and planned hydrogen refueling stations (HRS) were mapped during the project (Figure 8). Germany leads the Baltic Sea region with nearly 100 operational stations developed by H2Mobility, covering major metropolitan areas and highways. Poland has six operational HRSs with significant expansions planned by ORLEN, targeting 100 stations across Poland, the Czech Republic, and Slovakia. Both Norway and Sweden have several operational and planned HRSs, with Vireon AS and Everfuel aiming to construct extensive refueling networks and corridors to cover the Scandinavia. In Denmark, Everfuel has closed or paused its stations due to low demand, while Vireon AS plans to build new ones. Latvia has one refueling station in Riga supplying fossil-based hydrogen for municipal trolleybuses. Finland, Estonia, and Lithuania currently lack operational HRSs. In Finland, several stations are planned by P2X Solutions and Vireon AS, with the first expected to be operational by fall 2024. Estonia also has plans for its first refueling station by Alexela in 2024. Lithuania aims to install four public hydrogen refueling stations by 2026.

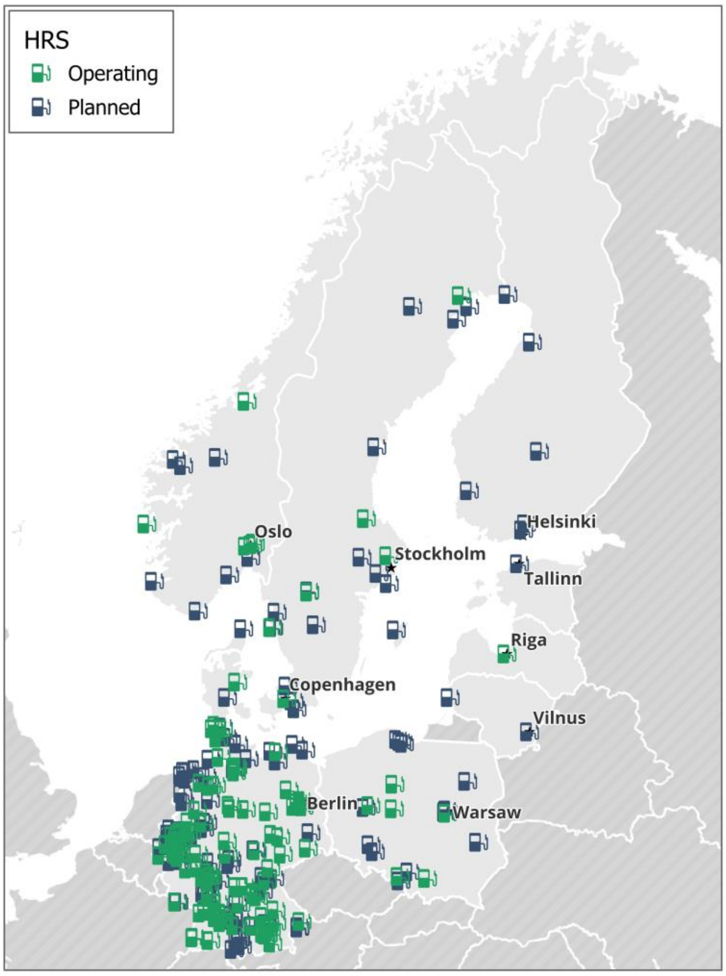

Figure 8. *Operating and planned hydrogen refueling stations in the Baltic Sea region* [8], [11].

3.4. Resource availability

3.4.1. Renewable electricity production

Renewable electricity is the key ingredient for hydrogen produced via electrolysis. In the context of the Baltic Sea region, the landscape for hydrogen production appears promising, with over **300 GW** of new wind and solar production capacity already in the pipeline based on analysis conducted in the BalticSeaH2 project. Data from publicly available sources was collected within the project to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational (Figure 9). Finland and Sweden stand out as frontrunners, with the largest volume of renewable electricity projects currently in development, totaling 125 GW and 120 GW respectively.

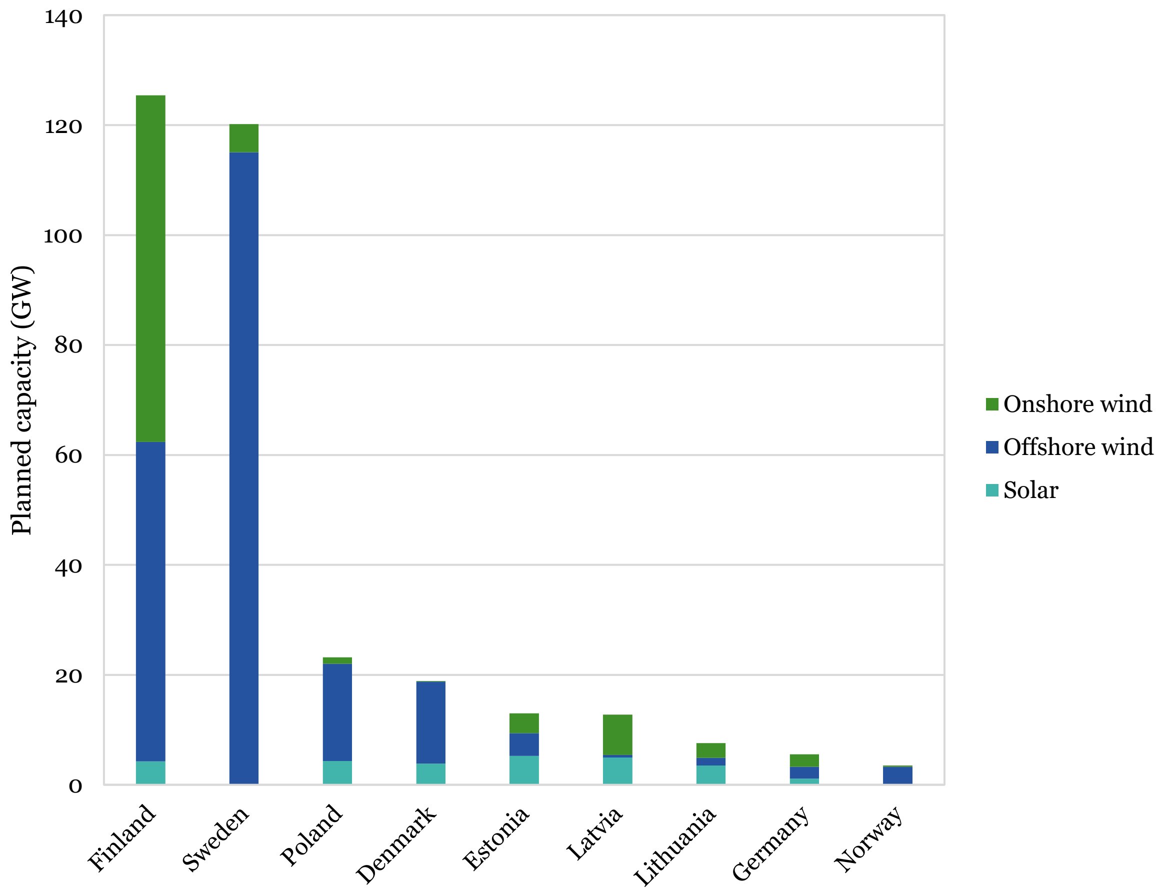

Figure 9. Renewable electricity projects in pipeline based on data collection conducted in BalticSeaH2.

3.4.2. Water

Hydrogen production also requires water for both production and cooling, with its impact varying by location and technology. Water scarcity can disrupt production, especially in water-stressed regions. In terms of water usage, steam methane reforming (SMR) is the most frugal, comparable to PEM electrolysis. Alkaline electrolysis and fossil hydrogen production combined with carbon capture, utilization, or storage (CCUS) increase specific water usage. Water usage intensity can be described using the Water Exploitation Index Plus (WEI+), with values over 20% indicating scarcity. At the national and annual level, the analyzed countries do not suffer from water stress. Norway exhibits the lowest level of water stress, followed by Sweden and Latvia, while Poland, Estonia, and Denmark are more water-stressed among the studied countries. It should be noted that calculating the WEI+ annually at the national level may not accurately represent the uneven distribution of resources across different areas and seasons, potentially concealing instances of water stress that are seasonal or regional. For instance, in the capital area of Finland, groundwater is not sufficient to meet all needs, while Finland's WEI+ at the national level is low (Figure 10).

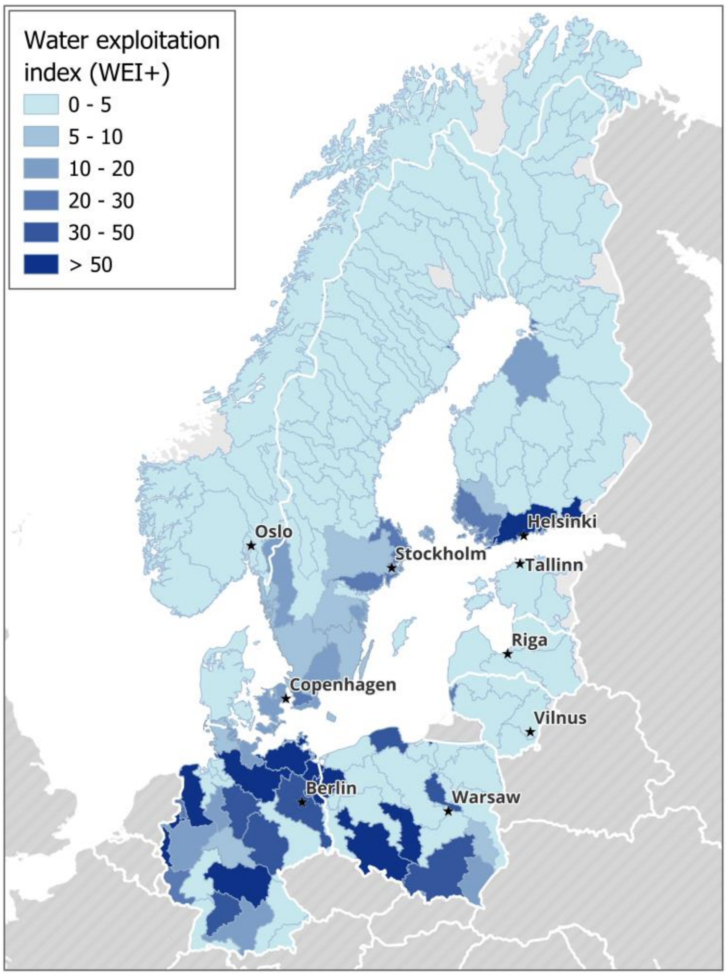

Figure 10. Regional WEI+ values for BSH2 countries in Q3, 2019 [12].

3.4.3. Availability of CO2

Further processing of hydrogen to other products, such as hydrocarbons, often needs carbon dioxide (CO2). Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries. Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important to untap hydrogen opportunities. Point sources of CO2 among the Baltic Sea countries is presented in Figure 11.

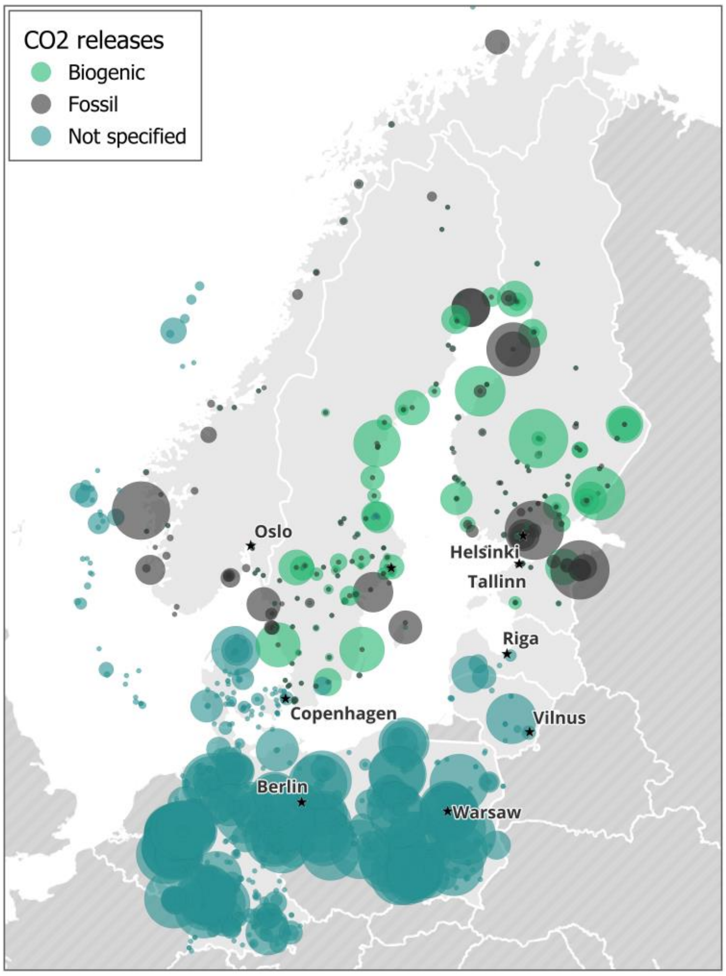

Figure 11. Locations of CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [13].

Finland and Sweden, with their strong forestry sectors, have numerous biogenic CO2 emission sources, positioning them well for different Power-to-X applications (Figure 11 and Figure 12). Finland emits 47 Mt/year of CO2, with 28 Mt/year biogenic, while Sweden emits 50 Mt/year, with 33 Mt/year biogenic. Poland (233 Mt/year) and Germany (379 Mt/year) have substantial CO2 emissions, mostly near large cities; however, the origin of the CO2 emissions was not specified in the data source. Denmark and the Baltic states (Estonia, Latvia and Lithuania) have smaller CO2 emission volumes, but specific regional concentrations can offer focused opportunities for Power-to-X applications. From CO2 storage perspective, Norway's continental shelf holds potential as a storage site for CO2 generated through the production of hydrogen via natural gas coupled with carbon capture and storage (CCS), and is seen as an important driver for hydrogen economy in Norway.

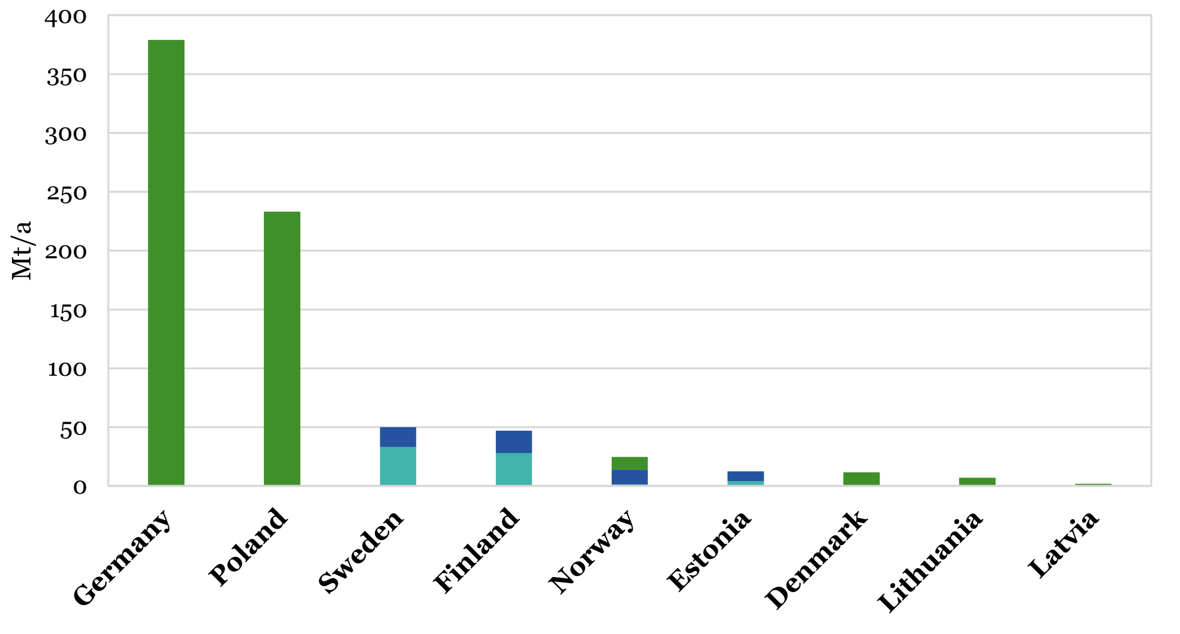

Figure 12. Total volumes of CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [13].

3.5. Infrastructure availability

3.5.1. Hydrogen pipeline transmission infrastructure

Hydrogen transmission infrastructure is undergoing active development within the Baltic Sea region (Figure 13). Gasgrid Finland and Nordion Energi are collaborating on the Nordic Hydrogen Route project, aimed at accelerating the hydrogen economy by establishing cross-border transmission pipelines between Finland and Sweden around the Bothnian Bay. Similarly, the Nordic Baltic Hydrogen Corridor project is focused on creating transmission infrastructure from Finland through Estonia, Latvia, Lithuania, and Poland to Germany. Additionally, the Baltic Sea Hydrogen Collector project is exploring the potential for offshore transmission pipelines to link Finland, Sweden, and Central Europe, facilitating clean hydrogen production for European demand.

In collaboration with Denmark and Germany, initiatives of Danish Backbone West and Hyperlink 3 projects are underway to establish hydrogen transmission infrastructure connecting Western Denmark with Northern Germany. Meanwhile, Germany has submitted a draft proposal for its national core hydrogen network, spanning 9,700 kilometers and primarily utilizing repurposed natural gas pipelines. This network aims to interconnect with various regions through projects such as the Nordic-Baltic Corridor and Baltic Sea Collector, thereby advancing the integration of hydrogen infrastructure across Europe.

Figure 13. Hydrogen infrastructure vision for 2030 [14].

3.5.2. Hydrogen storage

Hydrogen storage presents challenges due to its low volumetric density and hydrogen is often produced on-site with minimal storage capacity. With increasing clean hydrogen production and the need to integrate variable renewable electricity, substantial hydrogen storage expansion is required in the Baltic Sea region. This calls for a major increase in underground hydrogen storage (UHS), primarily in salt caverns, which are the most mature technology for pure hydrogen storage. Currently, no significant UHS capacity exists in the Baltic Sea region.

Some countries, like Estonia and Latvia, have limited potential for UHS due to low production and consumption levels as well as lack of suitable geological formations, focusing instead on smaller storage units for specific needs like mobility. Germany and Poland are exploring the adaptation of existing natural gas salt cavern storage sites for hydrogen. Germany is particularly well-positioned to become a central UHS hub due to its extensive existing gas storage capacity and favourable geology, planning significant expansions by 2030. Finland and Sweden lack suitable geological formations for salt caverns but are considering alternatives like rock caverns. Especially Sweden leverages its developed lined rock cavern (LRC) technology, with promising results from a pilot project linked to fossil-free steelmaking. Norway, with substantial hydropower capacity to balance the power grid, has theoretical potential in shut-down oil and gas fields but requires further research.

3.6. Hydrogen production plans

Mapping of announced clean hydrogen production projects in the Baltic Sea region took place from Q4/2023 to Q1/2024, with identified projects depicted in Figure 14. Based on the analysis and assumptions detailed in the country profiles, clean hydrogen production in the Baltic Sea region could potentially reach up to **6 Mt/a by 2030**, with Denmark (2 200 kt/a), Finland (1 450 kt/a) and Sweden (1 100 kt/a) leading the way. It should be noted that these figures are solely based on publicly announced projects, include uncertainties, and exclude plans with no indication of production volumes or capacities, thus providing only directional insight. Additionally, the data mapped for Germany primarily focused on facilities in North-East Germany and regions closest to the Baltic Sea, meaning the total volume does not encompass all German projects. Excluding Germany, the total volume of clean hydrogen production in the Baltic Sea region could reach up **5.7 Mt/a** by 2030. The current hydrogen production capacity, mainly fossil-based and excluding Germany, is **2.1 Mt/a**. Therefore, the hydrogen production capacity in the region could potentially triple if, under the assumptions applied, the announced projects were completed with the indicated production volumes or capacities. For more detailed analyses of hydrogen production plans, examples of the most advanced clean hydrogen projects at a national level, and the potential geographical areas for national-scale hydrogen economy developments, please refer to the country profiles.

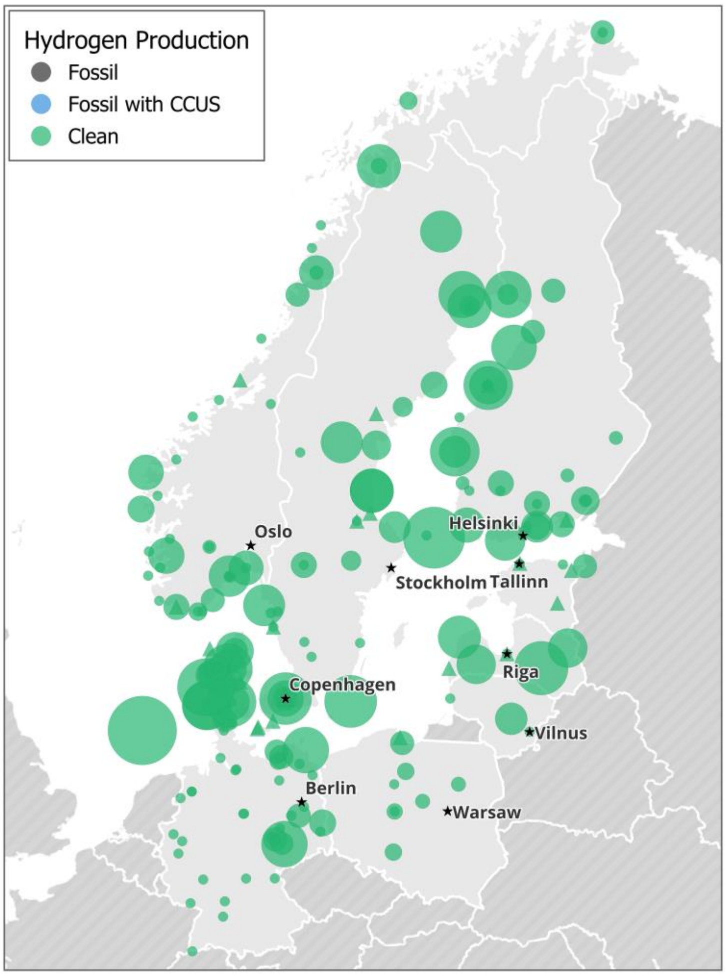

Figure 14. Operational and announced clean hydrogen production units and plans. Facilities with unspecified capacity indicated by triangle markers.

3.7. Education and employment

Across several countries among the Baltic Sea region, the educational landscape related to hydrogen technologies is expanding. Finland, Sweden, Germany, Norway, and Denmark offer relatively comprehensive education covering the hydrogen value chain, providing multidisciplinary degree and adult learning programs. The universities in Estonia and Poland incorporate hydrogen topics into their curricula, with an emphasis on management and broader energy and materials science programs. Contrarily, Lithuania and Latvia lag, with limited or no dedicated hydrogen programs, posing a challenge to developing a skilled workforce in these regions.

Employment opportunities in the hydrogen sector vary significantly across the countries examined, influenced by regional economic conditions and existing industrial activities. Finland faces labour shortages, particularly in the Uusimaa region, necessitating expanded education and international talent attraction to meet the demand for skilled workers. Sweden and Norway also experience a pressing need for technical professionals, especially in northern regions where significant hydrogen investments are underway. In Estonia, transitioning from oil shale mining in East Estonia, which has a high unemployment rate, to hydrogen-related jobs could address local employment challenges. Poland's industrial regions must adapt by reskilling the workforce to address decarbonization challenges, offering both risks and opportunities. Germany anticipates labour demand growth in construction and technology sectors linked to hydrogen infrastructure, while regions phasing out coal, like Eastern Germany, present opportunities for economic revitalization through hydrogen economies. However, Lithuania and Latvia face uncertain prospects due to limited educational programs and high unemployment in peripheral regions, potentially hindering the transition to hydrogen-based economies.

3.8. Public awareness and social acceptance

National perspectives for public awareness and social acceptance for clean hydrogen transition were also examined for the Baltic Sea region. With regards to social acceptance of hydrogen economy, the Baltic Sea region demonstrates a complex landscape. At a broader level, there is strong socio-political acceptance, driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization. On the other hand, on a community level, new green energy infrastructure, such as wind and solar power, have been met with opposition from locals, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries. In worst cases, community opposition has stalled or cancelled energy initiatives in the Baltic Sea region (e.g. community-rejection of wind power in Norway in 2019). However, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition (e.g. community-ownership models of wind power in Denmark) can effectively prevent such opposition.

A recent survey [1] also indicates diverging public awareness of hydrogen energy in the Baltic Sea region (awareness highest in Germany, lowest in Denmark), and awareness of the use of hydrogen specifically in industry settings is lower. This suggests further awareness-raising and exploration of public and community sentiments over hydrogen is needed to facilitate the successful deployment of the hydrogen economy.

4. Conclusions

This deliverable offers a comprehensive overview of each country's status, potential, and ambitions concerning the hydrogen economy in the Baltic Sea region. Specifically, it delves into the hydrogen landscapes of Finland, Estonia, Sweden, Norway, Denmark, Latvia, Lithuania, Poland, and Germany. Additionally, the profiles outline potential pathways for facilitating the transition to a hydrogen economy across relevant sectors while identifying readily available opportunities for hydrogen transition at the national level.

Various crucial aspects necessary for establishing a hydrogen economy on a national level are investigated in the country profiles. These include national hydrogen strategies and targets, the current state of hydrogen production and consumption, potential for emission reduction, identification of key sectors with clean hydrogen adoption potential, resource availability, infrastructure for hydrogen transmission and storage, clean hydrogen production plans, potential geographical areas for hydrogen development, and socio-economic factors influencing the hydrogen transition at the national level.

By offering a comprehensive understanding of each country's hydrogen landscape, the insights provided in the country profiles will serve as the foundation for the BalticSeaH2 Valleys vision work, that is to be conducted in the T2.2 "BalticSeaH2 Valleys' visions" of the BalticSeaH2 project.

5. Funding statement and disclaimer

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Clean Hydrogen Partnership. Neither the European Union nor the granting authority can be held responsible for them.

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The project is supported by the Clean Hydrogen Partnership and its members.

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Appendices A-I

Appendix A

Country profile Finland

Contents

Summary of national opportunities and challenges

Opportunties	**Challenges**
Availability and future potential of low-cost, clean electricity	Project delays due to rising interest rates, uncertainty about off-takers
Great potential for building new wind power capacity	Limited experience in hydrogen infrastructure
Resilient power distribution and transmission infrastructure and modern, reliable power grid	The social acceptance of clean energy technologies on local levels is weaker than on the national level
Carbon neutrality strategy and political will to lead in decarbonization and hydrogen development	Lack of domestic manufacturing competencies for electrolyzers, which could delay the uptake of clean hydrogen if larger markets consume all available electrolyzer capacity
Biogenic CO_2 and freshwater availability	The permitting and zoning processes for hydrogen infrastructure development are challenging
High-tech society and good track record in industrial energy solutions	High demand for new industrial zones, but access to suitable land areas and water for industrial sites is limited
Experience in fuel production and grounds for fossil-free steel production	Availability of skilled workforce, ability to attract foreign experts
Strong culture in public-private collaboration	Low public awareness and community opposition
Strong industrial will and collaboration to establish a leading hydrogen economy	
Stable and predictable political environment	
Socio-political acceptance driven by concerns over climate change, energy security, and a commitment to decarbonization	
Community-centered approaches and regional promoters facilitate hydrogen-related initiatives on regional levels	
Possibility to utilize the side product heat from electrolyzer e.g., the district heating	

National hydrogen strategies and targets

As of today, Finland does not have a national government-issued strategy related to hydrogen. However, in 2023, a **Finnish Government resolution on hydrogen** [1] was issued. The resolution is based on the Finnish Climate and Energy Strategy, industry dialogues, and internal preparations within the Ministry of Economic Affairs and Employment.

Hydrogen Strategy /Roadmap
No
Finnish Government resolution on hydrogen (2023)

The resolution outlines steps for developing the hydrogen economy in Finland, introducing policy measures and assigning their development responsibilities to relevant ministries. The aim is to create a competitive and predictable investment environment for Finland, targeting a leading position in Europe's hydrogen economy. According to the resolution, Finland aims to produce at least 10% of the European Union's emission-free hydrogen by 2030, emphasizing technological neutrality in its production. The hydrogen production targets leverage Finland's substantial potential for clean electricity. Achievement of significant hydrogen production capacity and refining levels over the next 10-20 years will require substantial investments, possibly reaching billions of euros, in clean electricity production, hydrogen production, refining, electricity transmission grid, hydrogen storages, and hydrogen network. As for hydrogen usage in the transport sector, the resolution set a target for e-fuels to cover at least 3% of all transportation fuels by 2030.

Quantified targets for hydrogen production
Yes
• 10% of the EU's emission-free hydrogen by 2030

Hydrogen cluster Finland (H2Cluster) has published **Clean hydrogen economy strategy for Finland** in 2023 [2], with the ambition for Finland to be the leading high-value hydrogen economy in Europe by 2035. The strategy states that the expansion of the global hydrogen market presents a significant economic opportunity of €16-34 billion per year for Finland by 2035, along with the possibility of generating over 60,000 new jobs. The strategy recommends actions and practical measures to ramp-up the development of hydrogen economy in Finland, while also providing related practical measures to address the existing barriers related to these actions.

National hydrogen roadmap for Finland was published by Business Finland in 2020 and produced by VTT. The roadmap provides an outlook of the hydrogen value chain in Finland, providing a foundation of knowledge for shaping Finland's hydrogen policy.

Other objectives

Finland's **Climate Change Act (423/2022)**, effective from July 1, 2022, mandates legally binding emission reduction targets: -60% by 2030, -80% by 2040, and at least -90% (aiming for -95%) by 2050, compared to 1990 levels. The Climate Act provides for the planning and monitoring of climate policy and national climate targets. The Act expands its scope to include emissions from the land use sector, emphasizing carbon sink strengthening. The objective of achieving a carbon-neutral Finland by 2035 is now written in law.

It is an established practice in Finland that each government draws up an **energy and climate strategy**. The energy and climate strategy considers and coordinates the Government Programme’s energy and climate policies, the long- and medium-term climate change policy plans referred to in the Climate Change Act, and the EU’s energy and climate targets for 2030.[3]

The Medium-term Climate Change Policy Plan up to 2035 (KAISU) under the Climate Change Act covers the greenhouse gas emissions of the effort sharing sector (i.e. non-ETS sector) - transport, separate heating of buildings, industries and energy production excluded from the EU ETS, work machines, waste, agriculture, and fluorinated gases - and includes a climate action plan and emission development estimates. The plan was approved by the Government in June 2022. According to the Climate Act, the Government submits an annual climate report to Parliament once a year to monitor the implementation of KAISU. The Ministry of the Environment coordinates the preparation of the KAISU and annual climate report. [4]

In accordance with the previous government’s Government Programme, sectoral low-carbon roadmaps were drawn up in cooperation with companies and stakeholder organizations in the relevant sectors. In all, 13 stakeholder organizations, including several industrial federations, prepared low-carbon roadmaps coordinated by the Ministry of Economic Affairs and Employment. The roadmaps were completed in summer 2020. The preparation was based on the principle that each sector knows their own sector best. The sectors were therefore responsible for the preparation and implementation of their roadmaps themselves. Prime Minister Orpo's Government Programme mandates the periodic update of low-carbon roadmaps in Finland and the aim is to have the roadmaps updated during the spring 2024. The goal is to ensure a current understanding of the situation and assess measures necessary to meet emissions reduction targets. These roadmaps allow sectors to share their perspectives on challenges and progress, aiding in the preparation of the new energy, climate, and industrial policies. [5]

At the beginning of 2023, a law entered into force that gives **priority to applications for permits** for investment projects important for the green transition in the period 2023-2026 in the permit procedure under the Environmental Protection Act and the Water Act at the Regional State Administrative Agencies. Priority is granted to projects involving renewable energy plants, offshore wind farms, industrial projects with renewable energy, hydrogen production (excluding fossil fuels), carbon capture/storage, and battery-related projects.[6]

National networks

Hydrogen Cluster Finland [7] is a network established of more than 100 industrial associations and companies aiming to promote hydrogen economy in Finland and to create business opportunities. They do this by information sharing, co-operation, and developing business perspective.

BotH2nia [8] is a network for actors interested in hydrogen. The objective of BotH2nia is to create a hydrogen cluster around the Gulf of Bothnia. It organizes hydrogen-themed events, disseminates information through its website, acts as a common platform for the evolving hydrogen industry in the north, and enables transparent, active dialogue between the members of the network. The network is open for businesses, academia, investors, municipalities, and cities.

Hydrogen Research Forum Finland (H2FINLAND) [9] is a forum of academic institutions involved in hydrogen-related research. It serves as a research-based forum for free and independent discussion and collaboration in hydrogen transition and research, promoting the development of a national hydrogen action plan, fostering research in the Finnish hydrogen economy, and enhancing the international impact of Finnish hydrogen research.

Hydrogen state-of-play

Finland is a very industry-intensive country in which fossil hydrogen is also produced, primarily for the refining industry (Figure 1). There is also small-scale electrolytic hydrogen production for industrial purposes. The annual dedicated hydrogen production in Finland is approximately **176 kt/a**, of which 1.6 kt/a is based on water electrolysis.

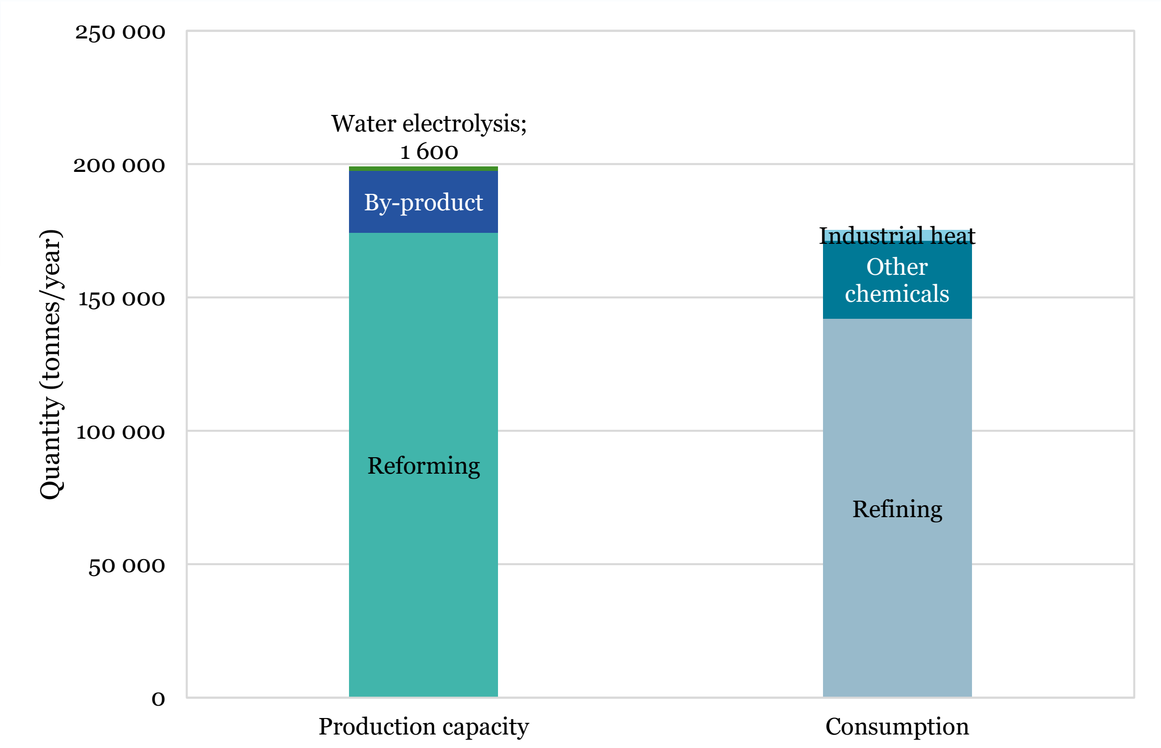

Figure 1. Hydrogen production and consumption in Finland [10].

Assuming that 174 kt/a of hydrogen is produced by steam methane reforming (SMR) with emissions of 9 $kgCO_2/kgH_2$, decarbonising Finland's fossil-based hydrogen production would lead to 1 550 kt of CO_2

reduction, which corresponds **3.4 %** of Finland's total CO_2 emissions (total emissions 2022: 46 040 kt CO2-eq excl. LULUCF [11]). The location of the operational hydrogen production facilities is presented in Figure 2.

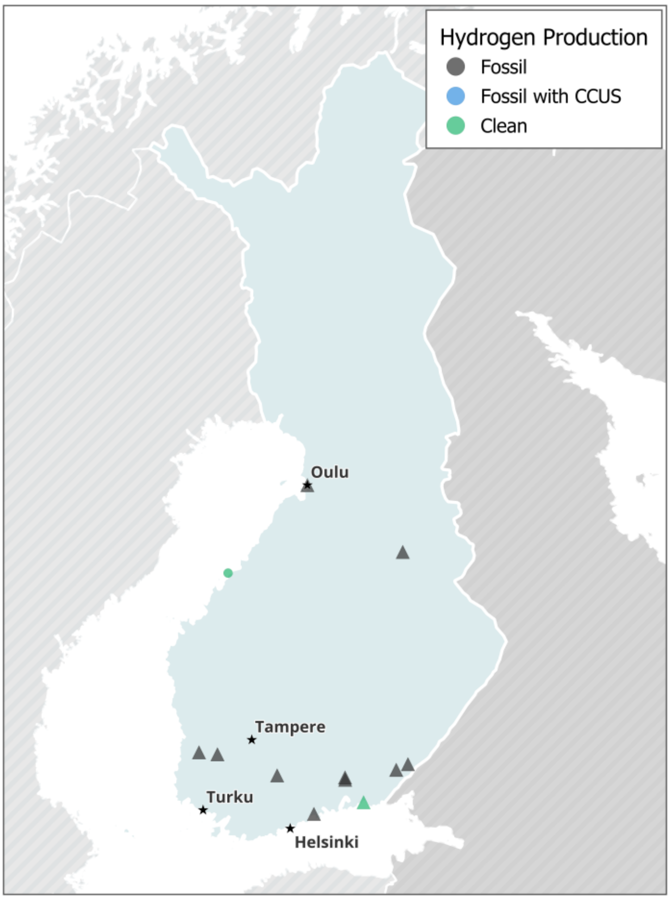

Figure 2. Operational hydrogen production facilities. Facilities with unspecified capacity indicated by triangle markers [12].

Existing hydrogen demand	CO_2 reduction potential in fossil hydrogen production
176 kt/a	**3.4%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [13]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel. [14]

Finland is a very industry-intensive country with decarbonisation potential in, e.g., steelmaking and oil refining, which can both be important drivers for clean hydrogen market in Finland. Finland has one oil refinery with capacity of 10.3 Mt of crude oil annually [15], located in Porvoo, in which fossil hydrogen could be replaced with a clean alternative. In fact, the refinery has plans for clean hydrogen production and is planning to build a 120 MW electrolyzer to produce clean hydrogen for the refinery processes [16]. The excess heat generated would also be recovered.

Finland has also one primary steel production plant of SSAB, located in Raahe, with annual steel production capacity of 2 600 kt/a [17]. SSAB is developing its HYBRIT technology, based on Direct Reduced Iron (DRI), and has recently revealed plans to build a new fossil-free mini-mill in Luleå, Sweden utilizing this technology [18]. Locations of these example industrial plants with potential for clean hydrogen use in decarbonisation are mapped in Figure 3.

Figure 3. Locations of example industrial plants in Finland with potential for clean hydrogen use in decarbonisation.

Ammonia production	Refineries	Steel production
No	**10.3 Mt/a (crude oil)**	**2 600 kt/a (steel)**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxis, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

Finland has certain geographical and legislative features that make hydrogen an attractive option in the mobility sector, especially in heavy road transport. The share of fossil fuels in the road transport is the second lowest among BSH2 countries (84%). Although Finland has a strong electricity grid and high growth prospects for clean electricity, which argues in favour of direct electrification of transport, much of its transportation is concentrated in remote areas. An example of such mobility use is related to the forest industry and its associated activities. Similarly, the most remote non-electrified railways could shift to hydrogen-powered trains if electrification is not feasible. The energy demand of the shipping sector is on the lower side of the Baltic Sea region (BSR) range. However, there is potential to also decarbonize this sector although it may not be the market driver for hydrogen demand in Finland.

Heavy duty transport in Finland is somewhat unique since a large portion of goods in Finland are transported with heavy configurations (60+ tonnes) compared to a maximum configuration mass of around 40 tonnes which is typical in Central Europe. Hydrogen integration to heavy configurations is not a challenge payload-wise since hydrogen is lightweight and the volume of storing hydrogen is not an issue. Finland even allows a higher configuration height (4,4 m) compared to Central Europe (4 m). The direct electrification of long-haul applications would require a large battery system which would result in a portion of the payload to be lost in terms of mass. In addition, hydrogen fuelling is relatively fast compared to charging a large battery and allows a long range with a relatively short stop.

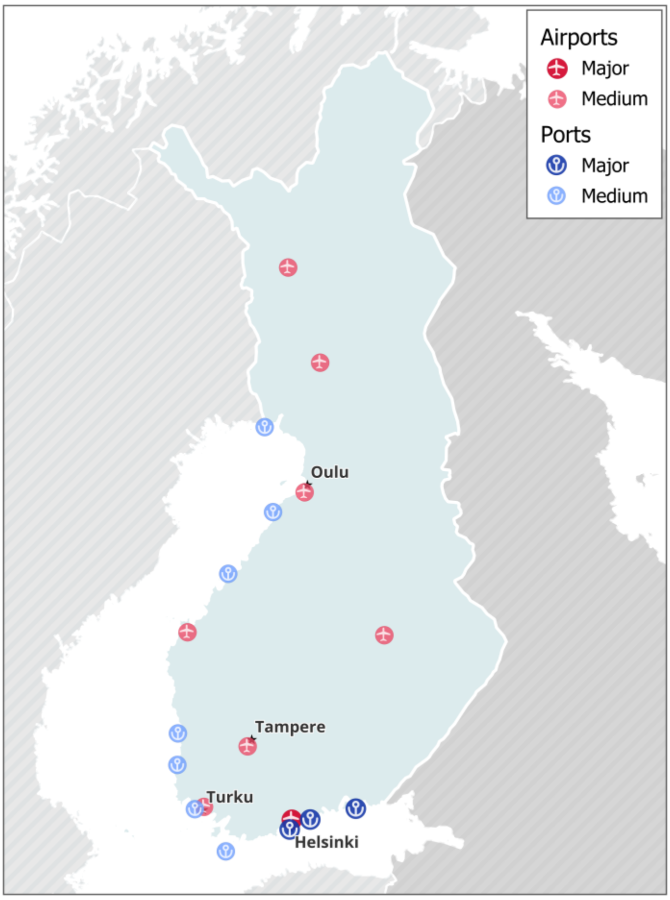

Figure 4. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) [19].

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
84%	**24% (19 ktoe)**	**118 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [20]

Hydrogen refueling infrastructure

As of today, there are no operating hydrogen refueling stations (HRS) in Finland (Figure 5). P2X Solutions Oy was the first to announce concrete plans to build HRS in Finland. The first station was planned to be built in Järvenpää to the immediate vicinity of the National Road 4 [21]. The initial plan was to have the station in operation during end 2024 but due to the changes in the operating environment, the final status and commissioning date of the station currently remain undetermined. The HRS was designed to accommodate multiple pressure levels, enabling the refueling of different vehicle types. The project is subsidized by the Finnish Energy Authority. The company will also construct a refueling station to Harjavalta, that will be integrated with the company's clean hydrogen production plant that is currently under construction.

Vireon AS, a subsidiary Norwegian Hydrogen, is also planning to build a hydrogen refueling network to Finland. The company plans to build a refueling station corridor from Northern Finland via Sweden and Denmark to the continental Europe. The company has recently (4/2024) received a 9.2 M€ grant from EU to aid building seven HRSs to Finland and Denmark, serving both heavy-duty and passenger vehicles [22]. The first refueling stations will be in Jyväskylä, Tornio, Liminka, and Vantaa. The HRSs in Jyväskylä and Vantaa are planned to be operational in 2025, while the refueling stations in Tornio and Liminka are scheduled for completion in 2026 [23]. The three additional refueling stations funded will be constructed in Denmark.

Vireon has partnered with Helen as part of its plans for a nationwide hydrogen refueling network [24]. Together, they are constructing a heavy-duty HRS in Vuosaari, adjacent to Helen's hydrogen production facility, as is being constructed as part of the 3H2 Helsinki Hydrogen Hub project. The 3H2 project received its final investment decision in April 2024. The HRS is expected to be operational by 2027.

Figure 5. Operating and planned hydrogen refueling stations [25], [26].

Resource availability

Renewable electricity production

The Finnish landscape for renewable electricity production looks promising, especially related to onshore wind power. As of November 2023, Fingrid, the Finnish Transmission System Operator, has received grid connection capacity inquiries worth over 300 GW to the main grid [27]. Most of these connection inquiries concern onshore wind power, but the role of offshore wind power and solar power has also increased; for offshore wind power, connection inquiries worth 95 GW have been received for the 2030s. The wind power capacity in Finland is growing rapidly (Figure 6); the cumulative installed capacity of wind power exceeded 1 GW in 2015, 2 GW in 2017, and by the end of 2023, the cumulative installed capacity reached 6.9 GW. If the environment for investments remains good, wind power is expected to cover more than half of domestic electricity production by 2030 [28]. The large and further increasing renewable electricity capacity implies low and competitive electricity prices in Finland, which is the most integral cost factor in hydrogen production via electrolysis. With electricity prices expected to be among the lowest in EU and combined by a highly reliable and cost-efficient power grid, Finland is one of the most promising locations to produce renewable hydrogen.

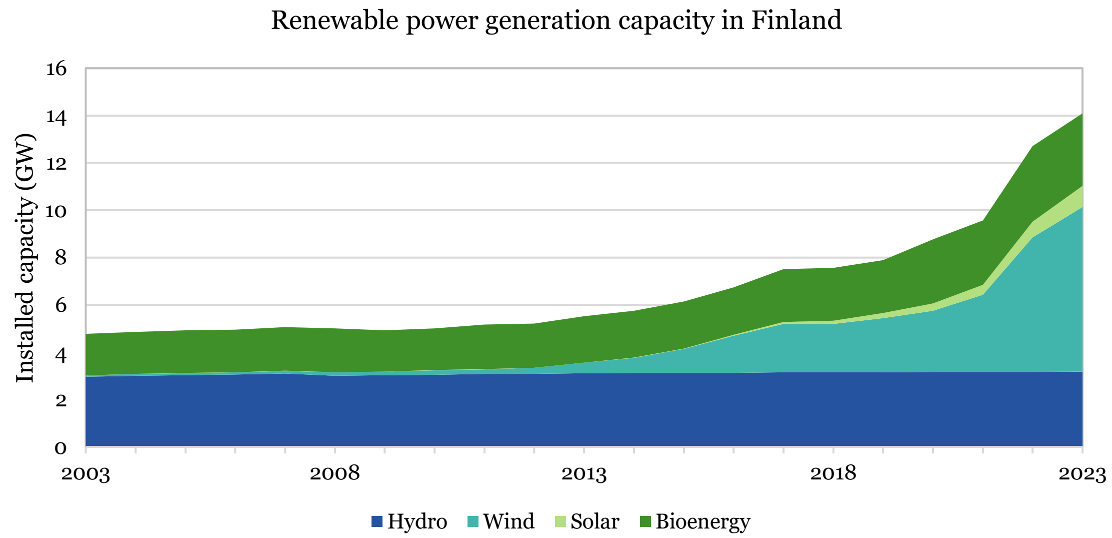

Figure 6. Cumulative capacity of renewable electricity in Finland (2003-2022) [29].

In addition to wind power, solar power has grown rapidly in recent years. By the end of 2022, solar power constituted 3% of the grid's electricity generation capacity, with 0.6% contributing to Finland's overall electricity production. The installed capacity of solar power was 635 MW. Small-scale photovoltaic setups (<1MW), dominate the grid-connected capacity. Industrial-scale solar plants (>1 MW) are on the rise, with a recorded 34 MW capacity. An extra 22 MW of PV capacity is estimated off-grid, primarily in leisure homes [30]. The installed capacity is growing exponentially, and by 2030, the installed capacity of solar power plants could be as high as 7 GW [31].

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects in Finland with a capacity greater than 10 MW and that are not yet operational. The mapped projects include 63.0 GW of onshore wind energy, 58.1 GW of offshore wind energy, and 4.3 GW of solar power, totaling in **125.4 GW** of new renewable electricity capacity in the pipeline (Figure 7).

Figure 7. Renewable electricity projects (GW) in pipeline in Finland based on data collection conducted in BalticSeaH2.

As a whole, renewable energy covers over 50% from the domestic electricity production in Finland: in year 2021, the share of renewables was 53% [32]. From the perspective of clean hydrogen production, it should be noted, that the share of nuclear power in Finland is significant. In the year 2021, the aggregate electricity production from nuclear and renewables was 86% from the total domestic electricity production.

The carbon intensity of the Finnish power sector was 130.98 gCO_2eq/kWh in 2022 [33]. According to the first Delegated Act (DA) [34] supplementing the recast Renewable Energy Directive 2023/2413 (RED III), the emission intensity of electricity should be lower than 18 gCO2eq/MJ (65 gCO_2eq/kWh) in the bidding zone for the grid electricity to be classified as fully renewable in renewable fuels of non-biological origin production (RFNBO). The carbon intensity of the Finnish grid from year 2022 does not consider Olkiluoto 3, a nuclear power plant with a nominal capacity of 1600 MW, which came online early 2023. Together with strong increase in renewable capacity, especially wind, the Finnish grid is expected to fall below the DA threshold. In practice, this would mean that hydrogen production in Finland could qualify as a RFNBO under the RED given that the temporal and geographical correlation, and power purchase agreement (PPA) criteria are met.

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 8 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

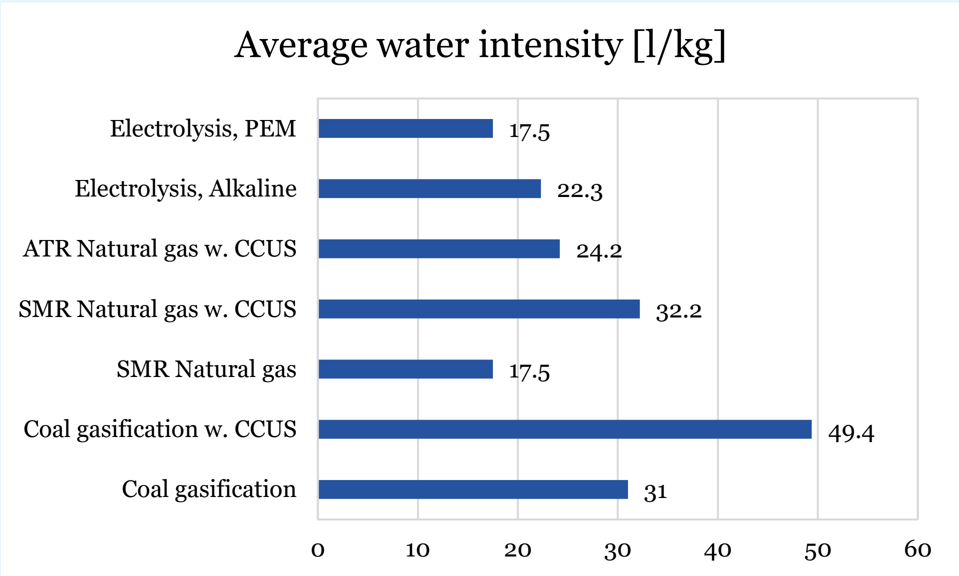

Figure 8. Average water consumption intensities by hydrogen technology [35].

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

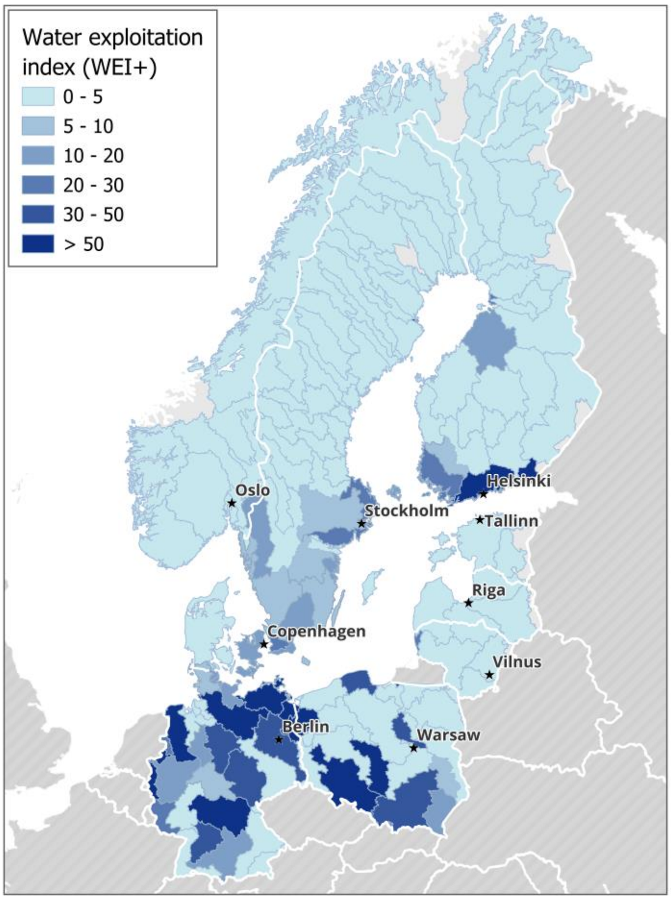

Figure 9. Regional WEI+ values for BSH2 countries in Q3, 2019 [36].

The local water stress conditions indicate that roughly 55% of the hydrogen projects that are operating or planned in Finland are in areas with low water stress, 45% are in areas with low to medium water stress. The expected hydrogen projects involving water electrolysis would raise hydrogen production in Finland by 1 450 kt/a (see *Hydrogen production plans*), which means an extra 29 million m^3 of water use (assuming average use of 19,9 l/kg between PEM and AEL). In general, Finland does not face water scarcity and its yearly WEI+ is 1.38% [37]. Although the national water situation is good, there may be local and seasonal scarcity of groundwater. In the largest urban areas, groundwater is not sufficient to meet all needs.

WEI+
1.38%
BSR range: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (<0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Finland has a strong forestry sector and thus, numerous biogenic CO2 sources, which is advantageous in power-to-x applications, such as synthetic fuel production. In Finland, the annual biogenic CO2 availability is 28 Mt/year, and fossil CO2 19 Mt/year (when calculating industrial sources larger than 0,1 Mt/year). Thus, the total annual CO2 amount is 47 Mt/year. Greatest fossil CO2 point sources can be found in Southern Finland and Western Finland (Figure 10). Biogenic CO2 sources are mainly located near the Finnish borders, and Central Finland. South-eastern Finland has quite many biogenic point sources, and some of them are quite significant in amounts. There could thus be possibilities for a CO2 hub or a power-to-x production plant.

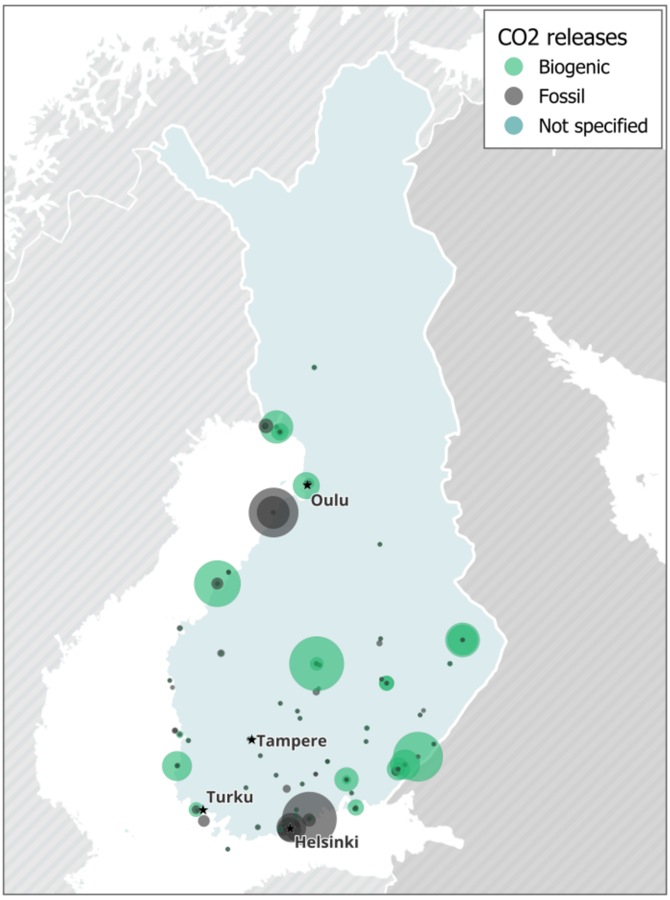

Figure 10. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [36].

Biogenic CO_2 availability
28 Mt/year

Infrastructure availability

Electricity transmission infrastructure

A strong and reliable electricity transmission system is essential for investments in both renewable energy and electricity-intensive industries. Fingrid, the Finnish transmission system operator for electricity, is responsible for the electricity system in Finland and the development of the main grid. Fingrid has published a main grid development plan in 2023 [38], outlining the development needs and planned investments for the main grid in the next ten years, with planned investments of approximately 4 billion euros. The main grid development plan is updated every two years in close collaboration with Fingrid's customers and other stakeholders to ensure it meets their electricity transmission needs.

According to the main grid development plan, the greatest needs for grid development in Finland will be in increasing the transmission capacity between electricity production and consumption centers, as well as in developing cross-border connections. A significant increase in electricity transmission from northern Finland and the west coast to southern Finland is anticipated. The increased transmission demand is driven by the electricity deficit in southern Finland caused by decreasing production from combined heat and power plants (CHP) and rising electricity demand. To offset this deficit, wind energy from the northern and western regions of Finland, where electricity production is to be concentrated, will be utilized. The importance of cross-border transmission lines is also growing to balance the rise in weather-dependent electricity production in Finland. Figure 11 illustrates the new 400-kV connections (marked in red) as outlined in the main grid development plan. The main grid development plan also includes detailed regional development and investment plans for the main grid.

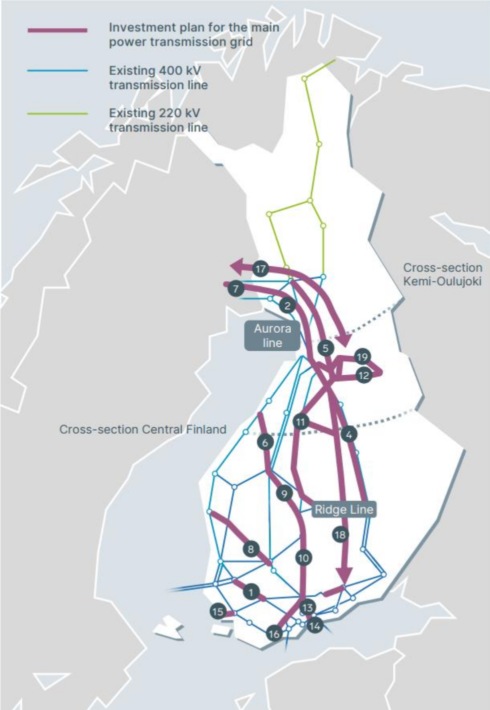

Figure 11. New 400-kV connections (marked in red) as outlined in the main grid development plan [38].

Fingrid also drafts long-term electricity system visions to provide long-term view of the development and reinforcement needs of the main transmission grid and to predict long-term changes in the Finnish electricity system. The visions highlight different phenomena in different future scenarios. The latest vision presenting Fingrid's four scenarios for electricity production and consumption trends up to 2035 and 2045, has been published in 2023 [39].

Fingrid and Gasgrid Finland, the country's gas transmission system operator (TSO), have jointly published a report titled "Energy transmission infrastructures as enablers of the hydrogen economy and clean energy system" in 2023 [40]. The report assesses the combined opportunities of electricity and hydrogen transmission infrastructure. In the study, three scenarios outlining different roles for Finland in the European hydrogen market have been evaluated. In all scenarios, the demand for energy transfer significantly rises as the production and consumption of both electricity and hydrogen become more widespread across Finland. The report emphasizes the importance of establishing a hydrogen pipeline transmission infrastructure to support the electricity transmission system to meet the energy transmission demand. Both organizations highlight the necessity of integrating the designs of hydrogen and electricity transmission infrastructures to create a cost-effective energy system and promote the hydrogen economy in Finland.

Hydrogen pipeline transmission infrastructure

In southern Finland, there is over 1,000 km methane pipeline managed by Gasgrid Finland, the country's gas TSO. This pipeline is linked with Estonia through a Balticconnector pipeline. For hydrogen transmission, new pipelines are envisioned to be constructed.

Gasgrid Finland develops the Finnish national hydrogen network via three large-scale cross-border hydrogen infrastructure development projects (Figure 12). The cross-border infrastructure development projects include 1) Nordic Hydrogen Route, designed for cross-border hydrogen transmission in the Bothnia Bay Region, 2) Nordic-Baltic Hydrogen Corridor, which aims to enable hydrogen transmission between Finland, Estonia, Latvia, Lithuania, Poland, and Germany and 3) The Baltic Sea Collector, which plans for an offshore hydrogen pipeline connecting Finland, Sweden, and Germany. All these pipelines are scheduled to become operational by 2030. In the next phases, the national hydrogen network can expand to cover wider parts of the country, including East, Central and North of Finland. [41], [42]

- **Nordic Hydrogen Route** – Bothnian Bay is Gasgrid Finland's and Nordion Energi's joint project to accelerate hydrogen economy by developing cross-border hydrogen transmission pipeline infrastructure and open hydrogen market between Finland and Sweden around the Bothnian Bay. The goal of the project is to enhance achievement of carbon neutrality targets, support regional green industrialization, economic development, and European energy self-sufficiency.

- The goal of the **Nordic Baltic Hydrogen Corridor** project is to develop hydrogen transmission pipeline infrastructure from Finland through Estonia, Latvia, Lithuania, and Poland to Germany. Gasgrid Finland focuses on the development of hydrogen infrastructure covering the whole Southern Finland and hydrogen market around the Baltic Sea Region.

- In **Baltic Sea Hydrogen Collector** project, the opportunity to build offshore hydrogen transmission pipeline infrastructure connecting Finland, Sweden, and Central Europe to enable clean hydrogen production for Europe's demand is studied. The project partners are Gasgrid Finland, Nordion Energi, and industrial companies OX2 and Copenhagen Infrastructure Partners. Gasgrid Finland focuses on enabling harnessing the wind resource potential at Finnish territorial water and market development at Baltic Sea Region.

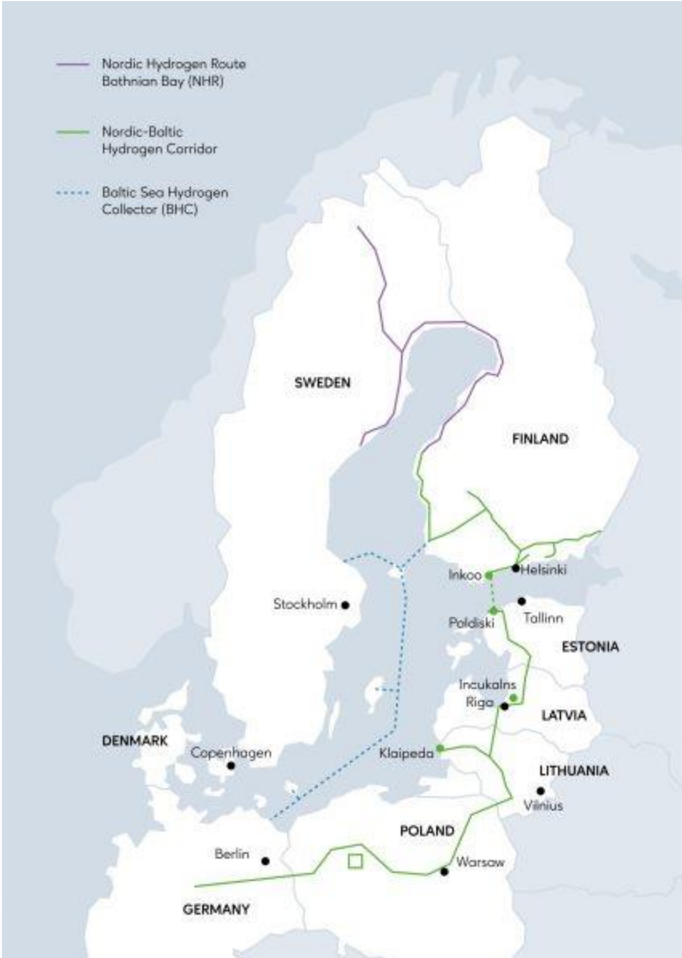

Figure 12. The on-going cross-border hydrogen infrastructure development projects in Finland [38].

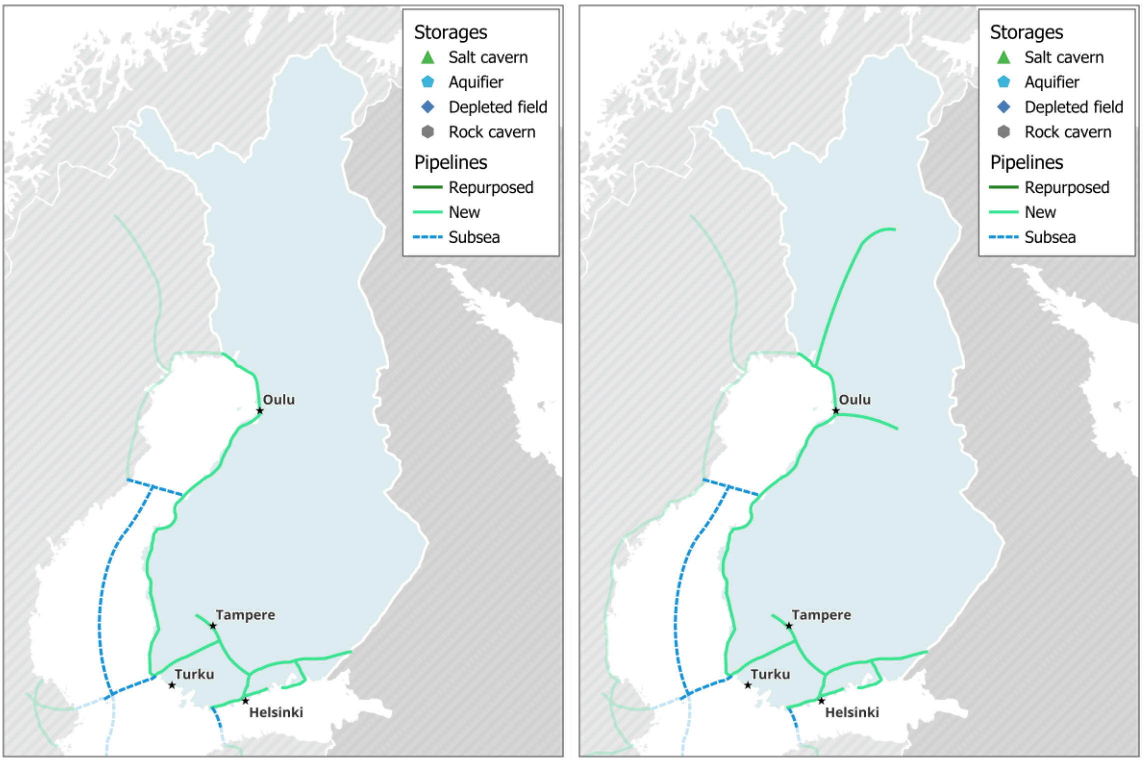

Figure 13. Left: A European hydrogen infrastructure vision for 2030, right: vision for 2040 [39].

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totalled 9.1 TWh in Europe, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [43]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing takes place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which only salt cavern has reached industrial maturity in storing pure hydrogen. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

When the share of variable renewable electricity production in the energy mix increases, the need to store and fully utilize the generated electricity increases. Compared to Norway and Sweden, Finland has a modest hydropower capacity [44], which limits the seasonal energy storing capabilities. From this perspective, converting electricity into molecules for long-term energy storage becomes more relevant. As of today, there is no large-scale hydrogen storage capacity in Finland. Presently, hydrogen consumption and production are local, with production and consumption occurring concurrently in a temporally synchronized manner. In the future if a national and cross-border hydrogen market develops, large-scale hydrogen storages become topical. Finland lacks salt formations for salt cavern technology, which is the cheapest and most common large-scale gaseous hydrogen storage technology. Considering the geological characteristics of Finland, a viable storage option are rock caverns. Additionally, the Finnish transmission system operator Gasgrid takes the needed storage capacity into account in hydrogen transmission pipeline design so that the transmission network can also store hydrogen, especially during the evolving hydrogen market. HYBRIT tests on 100 m^3 lined rock cavern storage in Northern Sweden have shown good results about its suitability for hydrogen storage [45].

Hydrogen production plans

As of today, Finland has two operational electrolytic hydrogen production units. One is located in Kokkola, where Woikoski Ab manufactures hydrogen for industrial applications. In addition, Tecoil produces small amounts of electrolytic hydrogen in Hamina for regenerating lubricant oils.

Many hydrogen projects are in progress, with a total estimated electrolyzer capacity of over **8.5 GW**. It is worth noting that one early-stage mega project "Långnäs Mega Grön Hamn" accounts for 3 GW of the planned capacity. In addition, some projects have not disclosed any information regarding their planned production capacities or volumes.

While not all projects have disclosed their individual capacities, they may have provided estimates of the annual hydrogen production volumes (kt/a). Assuming a 65% electrolyzer efficiency and year-round operational availability for projects that have only provided information of the expected electrolyzer capacity (MW), the combined electrolytic hydrogen production volume in Finland would surpass **1450 kt/a** by 2030. The current hydrogen production capacity in Finland is approximately 199 kt/a [12], indicating that if all currently planned projects were to be realized, Finnish hydrogen production capacity would increase more than sevenfold. It should be also highlighted that Gasgrid's market survey (as of 10/2023) shows even higher clean hydrogen production figures, above 2 400 kt/a of hydrogen by 2030 [46].

In the Figure 14 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project. As can be seen, the projects are primarily situated along the coastal regions of Finland, as well as in the southern part of the country.

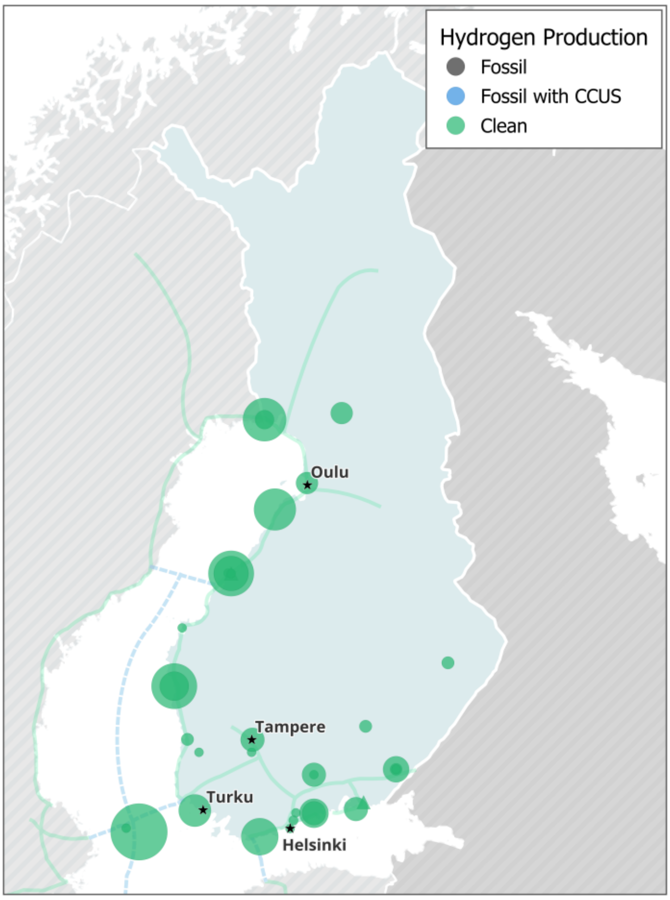

Figure 14. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

Based on public announcements, three clean hydrogen production projects have received final investment decision or are currently being constructed in Finland, with total electrolyzer capacity of **23 MW**:

- In Harjavalta, construction is underway for the country's first industrial-scale renewable green hydrogen and synthetic methane production facility, commissioned in 2024 by **PX2 Solutions** [47]. The plant will feature a **20 MW electrolyzer** and will include a methanation unit for synthetic methane production.

- **Hycamite** is constructing a methane pyrolysis facility in Kokkola for hydrogen production [48]. This facility will have an annual hydrogen production capacity of 2 kt along with 6 kt of carbon product. In the methane pyrolysis process, methane is separated into its elemental components, hydrogen and carbon, at elevated temperatures.

- The 3H2 - Helsinki Hydrogen Hub project, led by energy company **Helen**, reached its final investment decision in April 2024 and aims to construct a **3 MW pilot facility** for clean hydrogen production [49]. This facility aims to supply hydrogen for an on-site refueling station tailored to heavy-duty transport needs. The goal is to initiate hydrogen production at the new facility by 2026 and launch the refueling station by 2027. Additionally, surplus heat from the electrolyzer would be utilized in the district heating network of the capital area.

The cumulative capacity of clean hydrogen production projects in Finland is presented in Figure 15. Note that several large projects in early conceptual stages have not stated the planned commissioning year. In this case, the project is expected to be operational in 2030 or beyond. Additionally, projects without specified capacity or annual production volume are also excluded. Even with the exclusions, the trend is evident: Finland's hydrogen capacity would grow significantly. High production capacity in 2030 and later shows that many of the projects are still in initial phases and have not indicated the planned start-up year yet.

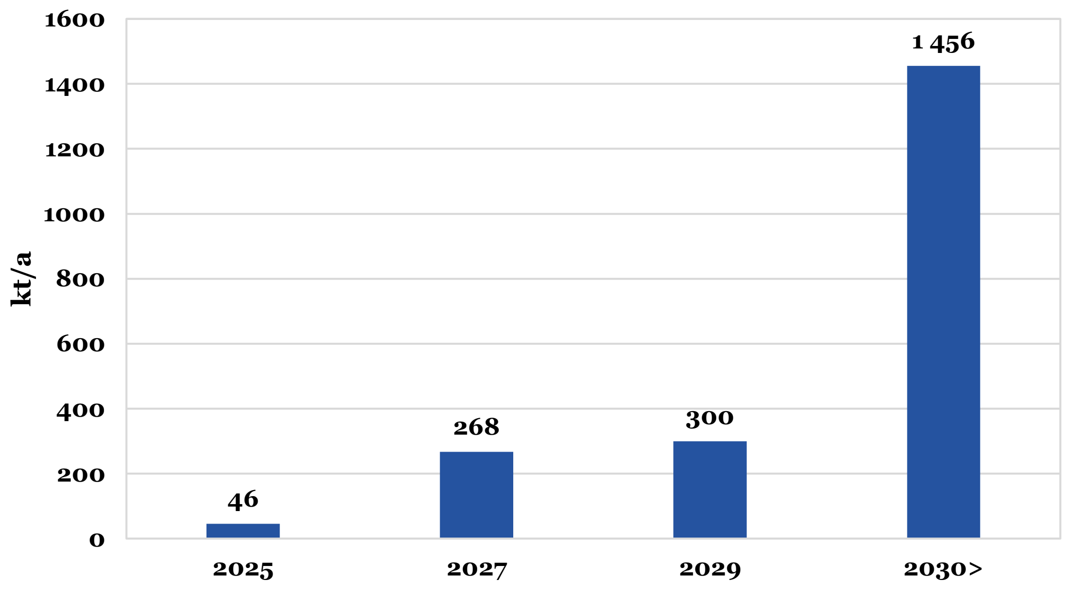

Figure 15. The cumulative capacity of clean hydrogen production projects in Finland based on data collection conducted within BalticSeaH2.

Potential geographical areas for hydrogen development

The following regions have been identified as the first-mover regions for hydrogen development in Finland with regional initiatives (i.e., Hydrogen Valley type of projects) under development or on-going:

Capital area and Porvoo: Main Valley in the BalticSeaH2 project. The largest hydrogen consumer in Finland, Neste, is located in Porvoo. The power and heat companies Helen Ltd and Vantaa Energy Ltd have initiated studies on the development of an industrial hydrogen valley in Uusimaa region together with Neste and Gasgrid Finland Ltd, the Finnish gas TSO. Both Helen and Vantaa Energy have individual projects and studies on producing and utilizing hydrogen in the capital area and integrating the hydrogen production with the heating sector. Within the scope of BalticSeaH2 project, several demonstrations will be carried out along the hydrogen value chain, including hydrogen production, distribution, storage, as well as several end uses, e.g., transport, energy, and industry.

Bothnian bay: Ostrobothnia and Bothnian bay benefits from vast wind power capacity development. North Ostrobothnia leads both in installed wind power capacity, as well as projected capacity additions; 41% of Finland's wind power capacity is located in this region, and 24% of the new investment decisions locate in the same region (status 1/2023) [50]. Central Ostrobothnia takes the second place in the new capacity additions with a 19% share. Additionally, the offshore wind projects in the exclusive economic zone of Finland near Kokkola sum up to at least 3.9 GW. Kokkola industrial area has existing hydrogen production and usage, as well as deep-water harbour equipped to handle, e.g., ammonia. Several large-scale hydrogen production and use projects have been published in the area, such as 350 MW and 1GW hydrogen and subsequent ammonia production by Flexens and Plug Power, respectively. On top of planned future projects, Woikoski Ltd operates 9 MW electrloyzers in Kokkola, and Hycamite TCD Technologies Ltd has a pilot plant there, where hydrogen is produced from methane via thermocatalytic decomposition.

Extending from Kokkola area to Bothnian bay, the area has several plants with potential for significant hydrogen usage, e.g., SSAB steel plant in Raahe, and Laanila industrial area in Oulu. The former has a potential to replace fossil coke, used as a reducing agent in smelting iron ore, to renewable hydrogen, which can be used in direct reduced ironmaking process. Laanila industrial area is producing and using hydrogen, and on top of that, Oulu and Kemi have large biogenic CO2 point sources, which could be utilized in, e.g., synthetic methane and methanol production together with hydrogen. Due to the large renewable electricity capacity in the area, there is a significant potential for hydrogen and hydrogen derivatives export, either through harbors, or hydrogen transmission pipeline, for instance. Nordic Hydrogen Route planned by Gasgrid would connect Swedish and Finnish regions in Bothnian Bay and create a large cross-border hydrogen valley in Northern Finland and Sweden.

Southeast: Hydrogen is used to produce, e.g., hydrogen peroxide, steel, and xylitol, as well as regenerate used lubricant oils. Large point sources of biogenic CO2 from pulp and paper industry: the biogenic CO2 emissions are approximately 10 Mt/a [51]. The wind power potential in the area is good, as the area is sparsely populated, and wind conditions are good. However, military air surveillance radars limit wind power permitting, and the power grid in the area would require additional capacity. To promote the development of hydrogen/power-to-x economy in Southeast Finland, an association called Hydrogen Valley Finland (Suomen Vetylaakso ry) was established early 2023.

Åland Islands: Åland Islands is also interesting location from the hydrogen perspective although there is no current hydrogen production in the region. The region has a gigawatt-scale offshore wind power potential, independent energy system and plans for green hydrogen and e-fuel production. Hydrogen and e-fuels could be used e.g., in shipping, local industry and in future local archipelago transport services. The Baltic Sea Collector offshore pipeline planned to be built between Finland, Sweden, and Germany can be connected to Åland Islands as well. This would enable hydrogen exports from Åland to Finland, Sweden, and Europe. The Åland Islands is part of a Smart Energy Åland [52] demonstration project, in which the aim is to demonstrate a society functioning with a 100% renewable energy, in which hydrogen is also envisaged to play a role.

Education and employment

The analysis by Hydrogen Cluster Finland concludes in their report from year 2022 that the educational landscape for hydrogen in Finland covers the entire value chain, with courses found in various programs. [53] However, becoming proficient in hydrogen economy requires knowledge from multiple disciplines. The interaction between electricity and hydrogen markets presents a significant question, prompting a need for expanded educational offerings. A comprehensive analysis of the educational offering related to wider hydrogen value chain can be found in the same report.

Wider modules regarding hydrogen are also available: Aalto University has received a two million euro grant to establish a hydrogen innovation center. Starting from 2024, there will be a multidisciplinary doctoral programme at the center to find solutions for the hydrogen economy, as well as two Master's programmes: multidisciplinary Advanced Energy Solutions and a brand new programme called Hydrogen and Electric Systems [54]. FITech offers hydrogen-related courses for adult learners and degree students. The FITech Hydrogen module consists of 20 – 40 ECTS, and it is organized by nine universities of Finland [55].

Hydrogen-related courses and modules meant for adult learners have been recently started: Ramboll Finland, together with VTT, provides five hydrogen courses (5 ECTS each) [56]. Additionally, Turku University of Applied Sciences and Vaasa University of Applied Sciences provide a 30 ECTS hydrogen module for adult learners, consisting of 5 courses [57].

While specific research data on hydrogen-related employment is unavailable, many labor market challenges extend to the hydrogen sector. Finland, particularly the Uusimaa region, faces significant shortages of highly skilled and professional workers. Current university and vocational school capacities are insufficient to meet regional labor demands, necessitating urgent expansion to address skills shortages. One of the main barriers to the growth for Finnish SME companies is the availability of skilled managers and employees [58]. Skills shortages play a major role in technology development and adoption. A recent wage survey with individual data also shows that the growth in wages of university graduates has accelerated more than other groups [59]. The acceleration in wage growth has been particularly strong for workers with tertiary degrees in science, technology, engineering, and mathematics who have changed employers. This finding suggests that firms are increasingly competing for workers who are often needed to develop and deploy new technologies. Ensuring an adequate supply of educational opportunities, flexible retraining programs, continuous learning pathways, and enhancing Finland's attractiveness to international talent are crucial steps to address these challenges.

The expansion of employment opportunities resulting from the emerging hydrogen economy is expected to be reflected in the increased export of hydrogen, e-fuels, steel, chemical products, technology, and services. Many of the additions on employment are therefore foreseen in areas that have already considerable industrial activity and infrastructure. On the other hand, areas that suffer from unemployment the most tend to be remote municipalities in Northern and Eastern Finland. The regions that exceed the whole country average unemployment rates (7.9%) are Päijät-Häme, Kymenlaakso, South Karelia, North Karelia, Central Finland, North Ostrobothnia, and Lapland [60]. Out of these regions, North Ostrobothnia is the leading region in terms of wind power capacity and has existing industry with potential to be coupled with hydrogen, e.g., steel industry and biogenic CO2 sources. In Southeast Finland, the role of forestry industry is significant in South Karelia and Kymenlaakso and thus, there is potential to couple hydrogen with bioeconomy. One promising solution to increase employment lies in co-locating renewable electricity and hydrogen production (and possible further refining or use) in the areas with high renewable potential. The creation of workplaces in these areas can also improve the local acceptance of wind power projects, which is expected to decrease in the coming years [61].

How hydrogen economy could help these areas is linked with the renewable electricity production potential; for example, Northern Ostrobothnia and Lapland have significant wind power potential, and if hydrogen production (and further refining) is co-located in these areas, it could bring additional welfare and jobs. The situation is more complicated in Eastern Finland - Eastern Finland does not have significant wind power capacity due to national defense requirements. Instead, solar power could enable renewable hydrogen production in such areas.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [62]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [63]. Recent survey [64] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [65]. The rise of right-wing politics and growing “greenlash” against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [66].

Another barrier potential barrier stems from a community-rejection (sometimes referred to as the NIMBY-effect, “Not In My Backyard”), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [67], [68], [69], [70], [71]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [72].

The success of this community ownership model in driving Denmark’s wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [64], [65] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

In the Finnish context, there remains little research on the socio-political and community acceptance of hydrogen technologies. In addition, a recent survey report indicates that the Finnish public is least aware of the use hydrogen in industry contexts (47%) [64]. However, growing amount of literature on wind power acceptance suggests that mitigating conflicts related to wind power can become a key factor in the successful deployment of hydrogen economy in Finland. Local opposition to wind power has increased in Finland, and the high speed, lack of political coordination, and the clear-cut geographical division of the placement of wind farms risks further increasing opposition. On the other hand, successfully and peacefully deployed wind farms in Finland have had similar characteristics: a good place-technology fit, collaboration between wind power corporations and local stakeholders from early stages of planning, fair compensations, and distribution of benefits to local communities [61].

However, in comparison to other Baltic Sea states, the Finnish public is among the most concerned about climate change, dependence on fossil fuels, and energy dependency on Russia [73]. Public acceptance of nuclear power is also among the highest in the Baltic Sea region, which could open routes to pink hydrogen as well.

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Appendix B

Country profile Estonia

Contents

Summary of national opportunities and challenges

Opportunities	Challenges
Estonia's national strategy aims to cover total electricity consumption with renewable energy production by 2030, transitioning from oil shale to wind and solar energy systems	No existing large-scale off-takers or industrial use cases limit the demand for green hydrogen
The advancement of offshore wind technology is seen as a key enabler for large-scale production of cheap and clean hydrogen, with over 150 wind turbines currently in operation and more expected by 2030	The hydrogen market in Estonia is still in its very early stages, lacking the necessary components for establishing a comprehensive hydrogen value chain
Agile and effective government, i.e. low bureaucracy	The current lack of green electricity supply for hydrogen production
Innovative and tech-driven: Estonia has the most start-ups valued at over 1 billion EUR per capita in the EU	The infrastructure for storage and transport of hydrogen is non-existent
Domestic fuel cell and electrolyzer manufacturing competences	Low public awareness of hydrogen and local opposition
Socio-political acceptance driven by concerns over climate change, energy security, and a commitment to decarbonization	Lack of engagement and benefit-sharing mechanisms with local communities
Regulations and funding mechanisms at an EU level help to support developments in the hydrogen sector creating momentum	Cost of green hydrogen is an issue compared to alternative solutions, as existing use of fossil hydrogen is limited and additional investments would need to be spent for any use cases

National hydrogen strategies and targets

The **Estonian Hydrogen Roadmap** [1], prepared by the Ministry of the Environment and the Ministry of Economic Affairs and Communications was published in 2023. The roadmap outlines the county's plan to develop hydrogen sector as part of its commitment to achieve climate, environmental and energy objectives. Although there is no current industrial hydrogen production or use in Estonia, the roadmap suggests making use of the opportunities related to hydrogen by encouraging renewable energy production and emerging hydrogen industries and services in Estonia. Via the development of hydrogen sector, the country could transform from energy importer to hydrogen and hydrogen technology exporter. The roadmap is set to be reviewed and potentially updated every three years.

The roadmap describes a three-stage plan for the development of the Estonian hydrogen sector:

- **Pilot phase 2021-2030** to develop policies, R&D and implement pilot projects and improve the availability of renewable energy, with at least 67 m€ allocated from state budget to support the development of local hydrogen technologies and 54 m€ to pilot green hydrogen value chains in the transport sector and chemical industry.
- **Scaling phase 2030-2035** to continue successful pilot activities and the development of value chain, removing identified barriers and improving the access to renewable energy
- **Expansion phase 2036-2050** to expand the Estonian hydrogen sector with abundant national renewable electricity available for other uses than local direct electrification

Hydrogen Strategy/Roadmap
Yes
Estonian Hydrogen Roadmap (2023)

The roadmap does not state quantified targets on hydrogen production. However, depending on electricity and hydrogen market developments, the roadmap evaluates the national hydrogen production potential to be 2 – 40 kt/a by 2030. In addition, the roadmap estimates that a minimum of 3-5 hydrogen refuelling stations with 2 kt/a capacity would be installed by 2030 at the latest.

Quantified targets for hydrogen production
No
Main indicators: • Hydrogen production potential 2 – 40 kt/a (2030)

National networks

Hydrogen Valley Estonia [2] is a group of Estonian organisations from both public and private sectors, as well as research institutions. The founders are Alexela, Eesti Energia, Port of Tallinn, the University of Tartu and the Estonian Association of Hydrogen Technologies. It aims to make the local energy system, which mainly relies on fossil fuels, more sustainable. The hydrogen valley has more than 30 local and international institutions in its support group, and it welcomes new members who are interested in joining. The hydrogen valley will make its strategy and work plan public to encourage collaborations among the parties.

Estonian Association of Hydrogen Technologies [3] was founded in 2016. It unites public and private stakeholders operating in Estonia, which are engaged in building the Estonian ecosystem through the development of hydrogen technologies, research and education, connecting market participants and government agencies, regulation and legislation building, funding activities and events. EAHT is a member of Hydrogen Europe and the European Clean Hydrogen Alliance and recognised as Estonia's national hydrogen representation body. The Estonian Hydrogen Association is the coordinator of Hydrogen Valley Estonia.

Estonian Hydrogen Cluster [4] The activities of the Estonian Hydrogen Cluster include gathering and disseminating information related to hydrogen production and application, raising awareness, coherent engagement and support of the public and private sectors, researchers and society, networking in Estonia and abroad, including support for Estonian hydrogen solutions to join European and global value chains, and supporting the development of the innovation ecosystem. Estonian Hydrogen Cluster is also a member of Hydrogen Europe. All companies, institutions and organisations interested in the application and research of hydrogen technologies are welcome to join the cluster.

Hydrogen state-of-play

Currently, there is no active commercial production or utilization of hydrogen, nor an established market for hydrogen in Estonia. Therefore, the hydrogen market in Estonia is still in its very early stages, lacking the necessary components for establishing a comprehensive hydrogen value chain. As of today, hydrogen is produced for research purposes in the University of Tartu. In addition, Eesti Energia utilizes hydrogen for the cooling of thermal power station generators [1]. Compared to neighbouring countries around the Baltic Sea, Estonian’s production capacity (25 t/a) and consumption (17 t/a) of hydrogen is practically non-existent (Figure 1). However, Estonia has several domestic electrolyzer and fuel cell companies, such as H2Electro (solid oxide electrolyzers), Elcogen (solid oxide elctrolyzers, BalticSeaH2 partnes), PowerUp (fuel cells, BalticSeaH2 partner), and Stargate (alkaline electrolyzers).

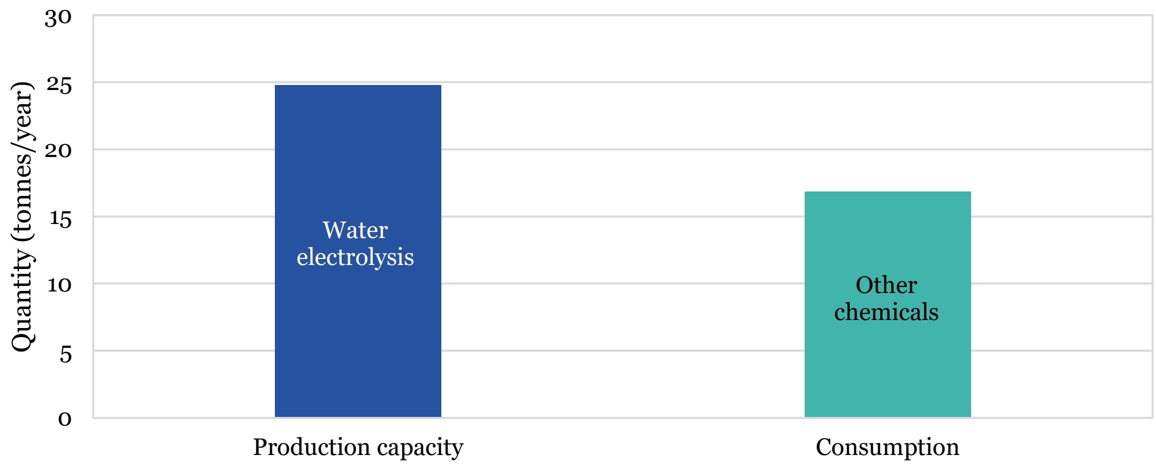

Figure 1. Hydrogen production and consumption in Estonia [5].

Existing hydrogen consumption sources	CO_2 reduction potential in fossil hydrogen production
No/very limited	**0%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [6]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2

emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel. [7]

Due to the lack of ammonia and methanol plants and refineries, there are no direct fossil hydrogen replacement alternatives in the industry sector in Estonia, which could be seen as low hanging fruit opportunities to foster the clean hydrogen transition. The final industrial company using fossil hydrogen for fertilizer production, Nitrofert, closed its operations in 2017 [1]. Potential hydrogen use in Estonia's heavy industry is primarily limited to oil shale refining, which has potential for utilizing clean hydrogen. However, as oil shale is anticipated to phase out as an energy source, this study does not consider it as an opportunity for clean hydrogen.

Ammonia production	Refineries	Steel production
No	**No**	**No**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxes, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

Clean hydrogen could be a viable option for the transport sector in Estonia, as it could power public buses or transport companies for short and long distances. Another possibility is to switch the regional trains to hydrogen-fueled trains, as most of Estonia's rail transport, 92%, relies on fossil fuels, which is the highest proportion among BSH2 countries. Ports can also use clean hydrogen for their activities;

they could become hydrogen hubs that provide fuel for ferries and bunkering operations. Port of Tallinn has a special potential to be a hydrogen hub, where clean hydrogen could power vehicles and equipment for transport and other uses. In addition, the port could offer hydrogen to ferries and other ships, as well as store clean hydrogen and related fuels like ammonia or ethanol.

Figure 2. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) [8].

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
96%	**92% (13 ktoe)**	**6 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [9]

Hydrogen refueling infrastructure

As of today, there are no hydrogen refueling stations in Estonia and hydrogen is not used in the country's transportation sector (Figure 3). An Estonian company Alexela is planning to open Estonia's first hydrogen refueling station in 2024 [10]. The refueling station will consist of two sites, of which one is set of supply hydrogen for passenger cars and the other for heavy-duty vehicles. Alexela will also build public green hydrogen refuelling stations in Tartu and Sauga as part of a recently funded project with Enefit Green, Go Bus, and Eesti Energia [11].

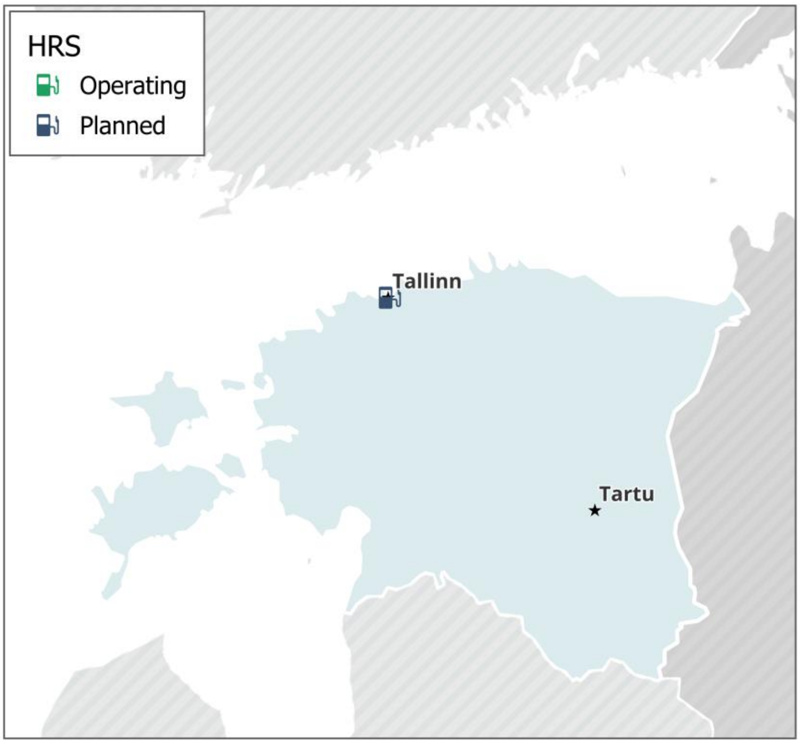

Figure 3. Operating and planned hydrogen refueling stations based on *[12], [13] and publicly announced projects.*

Resource availability

Renewable electricity production

The national strategy for Estonia is to cover total electricity consumption with renewable energy production by 2030, moving away from oil shale, towards a system based on wind and solar. There are enough onshore wind projects in later stages of development to meet this target by 2030, with an informal target aiming for 120% and ambitions to develop the offshore wind sector, to account for growth in electricity demand. The development of offshore wind will be the key enabler for large-scale production of clean hydrogen. In early 2024, Estonian Climate ministry has proposed a Contract for Difference (CfD) support mechanism to foster the development of 4 TWh on onshore and 4 TWh of offshore wind energy [14].The recent trends in renewable power generation capacity in Estonia are illustrated in Figure 4. Especially notable is the considerable rise in solar production capacity, which has multiplied significantly, reaching 535 MW by the end of 2022 [15].

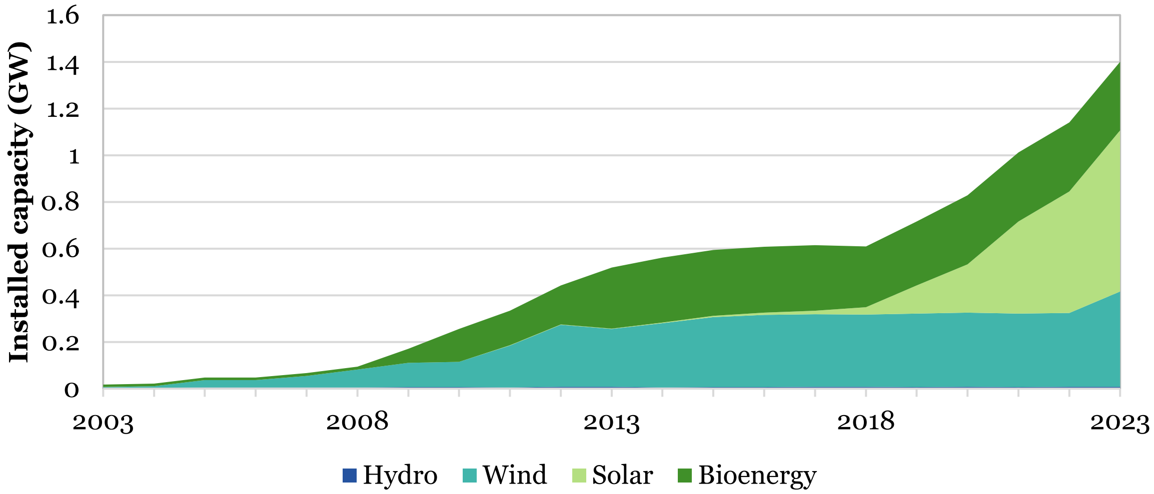

Figure 4. Renewable electricity generation capacity in Estonia between 2003-2022 [14].

Estonia has a high potential for wind energy. To date, Estonia has over 150 wind turbines with a capacity of 359 MW in operation and 325 MW under construction and expected to be operational in 2024 *[16]*. Several projects are on the horizon, including offshore wind development in the Gulf of Riga and around Saaremaa, with approximately 285 wind turbines expected to be installed with a total generation capacity of 2 GW by 2030 *[15]*. Investments into renewable energy generation could be used for clean hydrogen production.

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. As for Estonia, these projects include 5.3 GW of solar energy, 3.6 GW of onshore wind energy, and 4.1 GW of offshore wind energy, totaling **13 GW** of new renewable electricity capacity in the pipeline (Figure 5). The enourmous growth potential of renewable electricity production becoming an enabler for cheap, clean hydrogen production is an important driver for the clean hydrogen sector in Estonia.

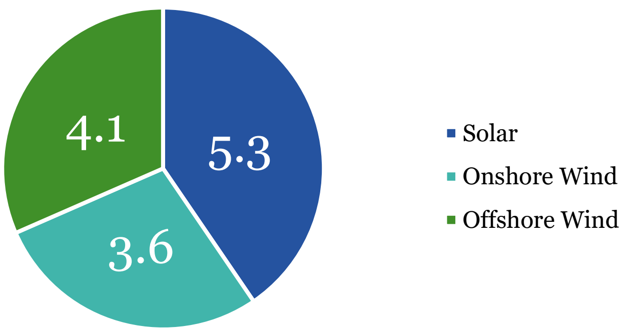

Figure 5. Renewable electricity projects (GW) in pipeline in Estonia on data collection conducted in BalticSeaH2.

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 6 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

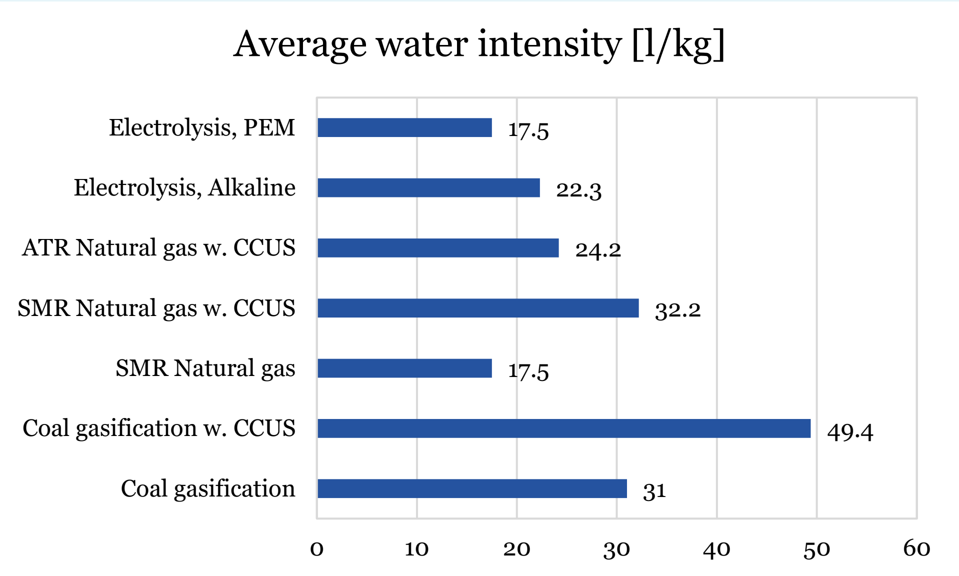

Figure 6. Average water consumption intensities by hydrogen technology [16]

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water abstraction to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

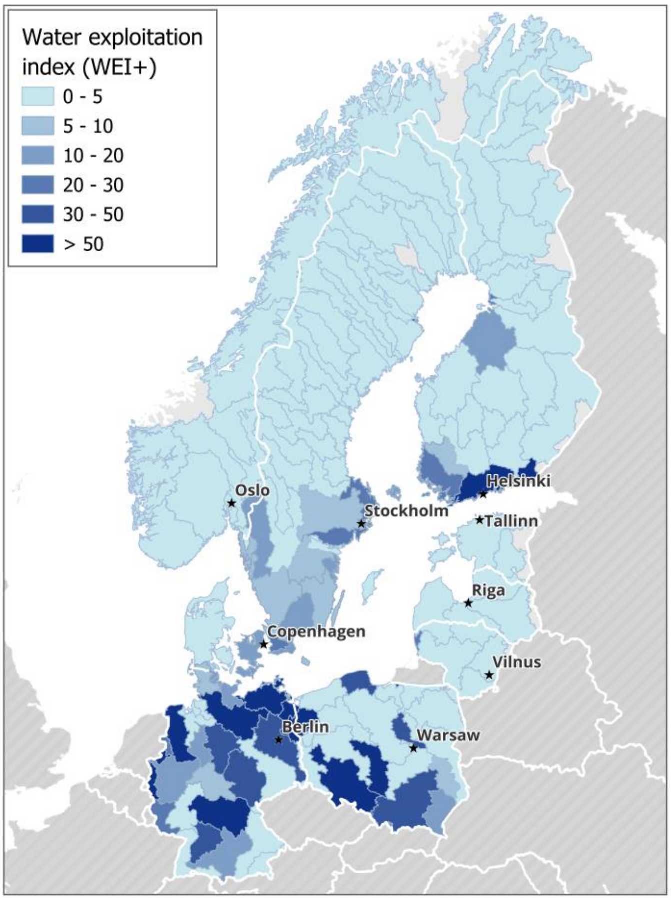

Figure 7. Regional WEI+ values for BSH2 countries in Q3, 2019 [17].

In general, Estonia does not face water scarcity at the country level, neither does it have areas that significantly differ from the national general view. The expected hydrogen projects involving water electrolysis would raise hydrogen production in Estonia roughly by 20 kt/a, which means an extra 0.4 million m^3 of water use (assuming average use of 19,9 l/kg between PEM and AEL).

WEI+
5.44%
Baltic Sea region: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO_2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO_2 feedstock. Biogenic CO_2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO_2 sources in the region are important for hydrogen opportunities. The CO_2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO_2-concentration in the stream, allowing a lower cost and less effort in the CO_2 capture. The sources of CO2, or possible CO_2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO_2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO_2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO_2 emissions. Annual CO_2 emissions including smaller plants (< 0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Estonia has a total of 12.5 Mt/year of CO_2 emissions (when calculating industrial sources larger than 0,1 Mt/year), of which the share of biogenic CO2 is 3.9 Mt/year, and fossil CO_2 8.6 Mt/year. The amount can be seen as relatively small compared to some other countries, and mostly it consists of fossil CO_2. Most CO2 sources can be found in the Northeastern corner, the fossil CO_2mostly in Narva, and the biogenic near Kohtla-Järve (Figure 8). Since the CO_2 is mainly found in the Northeast, it would probably be the most likely location for CO_2 utilization. More specifically, Kohtla-Järve would be an interesting area for power-to-x production, since the CO_2 is of biogenic origin.

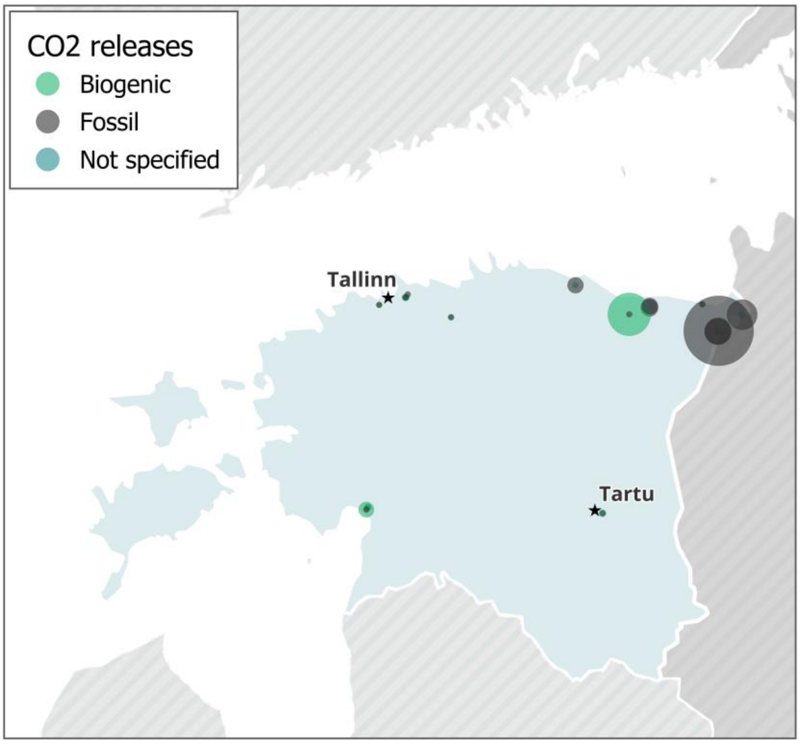

Figure 8. CO_2 emissions from industrial facilities and large combustion plants exceeding 0.1 Mt CO_2/year [18].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

Elering, the electricity and gas transmission system operator in Estonia, manages a network of natural gas pipelines spanning 977 kilometers, which also incorporates an underwater link Balticconnector to Finland. The envisioned hydrogen transmission pipelines are planned to be located in regions where no natural gas pipelines exist and hence repurposing the pipelines is not seen as an alternative [19].

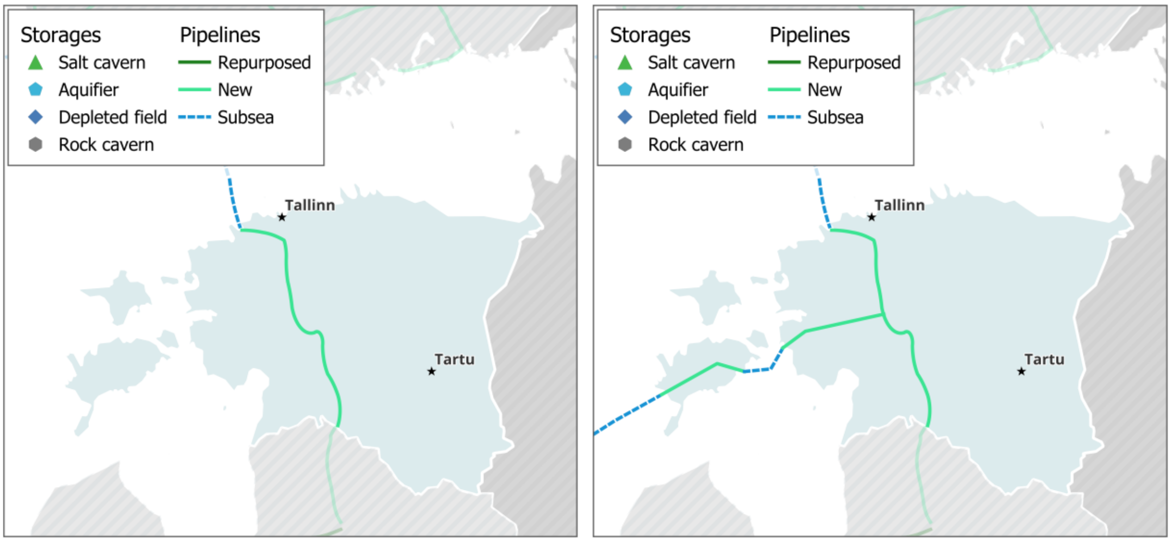

Figure 9. Left: Hydrogen infrastructure vision for 2030. Right: Vision for 2040 [20].

Elering is involved in a project **Nordic-Baltic Hydrogen Corridor** (Figure 10), to establish a hydrogen transmission pipeline between Finland, Estonia, Latvia, Lithuania, Poland, and Germany. In addition to Elering, the involved parties in the project are Gasgrid, (Finland), Conexus Baltic Grid (Latvia), Amber Grid (Lithuania), Gaz System (Poland), and ONTRAS (Germany) [20]. The cross-border hydrogen transmission pipeline is scheduled to become operational by 2030.

Prior to increasing the generation of renewable energy and hydrogen, Estonia is being considered as a possible pathway for transmitting hydrogen from Finland, through the Baltics and Poland, to Germany. In late 2030s, when the offshore energy and hydrogen production is expected to ramp up in Estonia, there is an opportunity to build a new hydrogen transmission pipeline to the islands off the west coast of Estonia to transmit hydrogen produced there and connect these pipelines to the **Baltic Sea Hydrogen Collector**. In the Baltic Sea Hydrogen Collector project, the opportunity to build offshore hydrogen transmission pipeline infrastructure connecting Finland, Sweden, and Central Europe to enable clean hydrogen production for Europe's demand is studied. The project partners are Gasgrid Finland, Nordion Energi, and industrial companies OX2 and Copenhagen Infrastructure Partners [19].

Figure 10. The Nordic-Baltic Hydrogen Corridor [20].

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [21]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which only salt cavern has reached industrial maturity in storing pure hydrogen. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

Estonia does not have any existing hydrogen storage capacity, and the possibilities for building large-scale capacity are somewhat restricted. The main consumption of hydrogen is expected to occur in areas with high population and urban density, such as Port of Tallinn, which reduces the availability of suitable locations for storage development. Moreover, the estimated hydrogen production and consumption levels in Estonia are relatively low with the greatest anticipated demand in mobility. Therefore, the storage capacity required is likely to concentrate on smaller storage units that provide hydrogen for mobility and port operations.

Hydrogen production plans

Currently, there is no active commercial fossil nor clean hydrogen production or utilization in Estonia. Several small-scale projects have received state support from the Environmental Investment Centre (KIK) of Estonia for their clean hydrogen projects, for which they needed to demonstrate the whole of the value chain. Many of the projects are related to clean hydrogen production for transportation.

The first project from Utilitas and Alexela received support in 2021, with the project having to achieve readiness by September 2024 to receive support. The second round of projects, specifically aimed at hydrogen use in the transport and chemicals sectors (projects 2-5) received confirmation of €40.5M support in December 2023 [22], with the projects having to come online by 2026.

1. **Utilitas (with Alexela)** – will receive €5M to develop a clean hydrogen production facility at their Väo cogeneration plant, with two hydrogen refueling stations near Tallinn to fuel local taxis.

2. **Port of Tallinn (with Green Marine & Alexela)** – will receive €9,9M support for their €13.7M project to produce clean hydrogen and hydrogen refueling station for 8 hydrogen vehicles and potential use in the marine sector.

3. **Eesti Energia (with Alexela, Enefit Green and GoBus)** – will receive €9.9M support for their €12.5M project to produce clean hydrogen from Enefit's Purtse hybrid wind and solar farm and set up two hydrogen refueling stations to fuel 3 buses, 8 cars and two trucks.

4. **Utilitas (with Alexela)** – will receive €4.1M for their €5M project to expand on their previous development, expand clean hydrogen production and set up an additional hydrogen refueling station.

5. **Derivaat NH3** – will receive €16.9M support for their €70.4M project to produce clean hydrogen for green ammonia production, at their facility in Paldiski.

The current projects have limited public information on their planned hydrogen production capacities. The "Voyager 1" green ammonia project by Derivaat NH3 is announced to have annual hydrogen production capacity of **4 kt/a** [23]. In addition to the previous list of projects, Eesti Energia has initial plans for the use of hydrogen as a strategic reserve on the electricity network. The early plan is to develop a **100 MW** peak power plant to Narva by 2030 [24]. The power plant could utilize hydrogen, biomethane and natural gas as fuel. Based on the experience from the first peak power plant, a second one could be built to Iru with same parameters. Eesti Energi can either produce hydrogen or buy it.

In the Figure 11 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project.

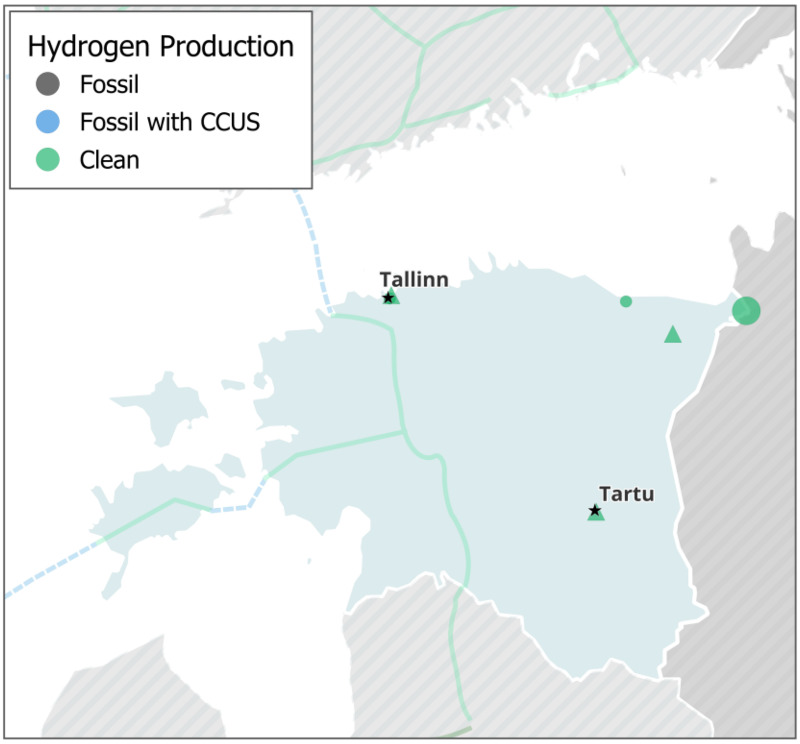

Figure 11. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

Potential geographical areas for hydrogen development

North Estonia (Harju and Rapla County): North Estonia offers advanced and rapidly developing production infrastructure – roads, telecommunications, warehouse facilities, etc.; and a compatible transportation network with easy access to the Tallinn international airport, railway, and several passenger and cargo ports (the largest cargo port being Muuga Harbour). The region's beneficial business environment for industrial, global business services and supply chain sectors attracts foreign direct investments from global multinationals as well as European companies of different sizes. As a supply chain hub, it is logical that hydrogen supply chain operations are centred in North Estonia near the main transportation hubs (airport, shipping, and road/rail transport).

South Estonia: (Tartu, Viljiandi, Polva, Valga, and Võru counties): South Estonia is like a small model of Estonia, where the region's development revolves around the city of Tartu – ICT and startup ecosystem, higher education, and healthcare keep providing many profitable jobs. The South Estonian economy continues to be driven by the timber and food sectors. Throughout its history, South Estonia has traditionally been a rural area – plenty of forested areas and fertile farmland. Companies in Southern Estonia develop and use wood-based materials and have become top performers in this field, for example, helping Estonia achieve its position as the largest exporter of wooden houses in the EU. South Estonia is the academic centre of Estonia with the University of Tartu. Here, there is the potential to develop and test new hydrogen applications. Also, it could be an interesting location to train workforce for the hydrogen sector.

West Estonia (Pärnu, Lääne, Saare, and Hiiu countries): Economic activity has been successful in conventional fields – forestry, wood processing, agriculture, (eco)food industry and tourism- greatly influenced the region's prosperity. West Estonia also includes the Island communities and the Gulf of

Riga. Here, Blue economy jobs drive the economy and include small craft construction, aquaculture and offshore energy. Particularly relevant is offshore wind energy development. The most relevant hydrogen application is clean hydrogen production from offshore wind energy.

East Estonia (Ida-Viru, Lääne-Viru, Jõgeva, Järva counties): East Estonia is an industry-orientated area with plenty of space available near logistical and natural resources. The timber industry, the manufacture of building materials, energy and the metal industry have an essential role to play in the region's economy. Particularly relevant is the oil shale mining and refining which takes place in this region. Here, the oil shale industry uses 30 t/a of fossil hydrogen. It is possible to substitute fossil hydrogen for clean hydrogen or implement carbon capture technology to develop blue hydrogen.

Education and employment

The University of Tartu offers programmes that have courses on hydrogen, for example M.Sc. Materials Science and Technology. Tallinn University of Technology has hydrogen-related education in M.Sc programme Green Energy Technologies [25]. Also, the university has created a hydrogen scholarship with Elcogen, an Estonian SOFC and SOEC technology provider [26].

There is no specific research data on hydrogen-related fields in Estonia. In the short term, Estonia might need more engineers and workers for developing hydrogen infrastructure, while in the long term, new ways of using hydrogen for transport and distribution might require re-training workers for safely operating and using hydrogen applications.

East Estonia has a high unemployment rate. This is especially relevant for the oil shale industry that is being phased out. Oil-shale mining has historically provided many jobs, but since it is being phased out, hundreds (maybe thousands) of workers will be impacted by this.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [27]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [28]. Recent survey [29] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [30]. The rise of right-wing politics and growing "greenlash" against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [31].

Another barrier potential barrier stems from a community-rejection (sometimes referred to as the NIMBY-effect, "Not In My Backyard"), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [32], [33], [34], [35], [36]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [37].

The success of this community ownership model in driving Denmark's wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [29], [30] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

In the Estonian context, literature on the socio-political and community acceptance of hydrogen technologies is still sparse. However, a recent study outlined that the main problems with social acceptability of hydrogen are people's low awareness of hydrogen use and the fear and ignorance of previous accidents [36], suggesting a need for increased awareness-raising activities.

Although opposition to wind power is not as prominent in Estonia as it is in most Baltic Sea region states, a lack of systemic consultation with local actors, and lack of energy community frameworks provoked opposition to other energy reforms in Estonia and can become key challenges in the planning and deployment of hydrogen economy [35]. In contrast to other EU Member States, the Estonian public is also reported to be less concerned than other EU Member States about air pollution and greenhouse gas emissions [27], which can translate to lower socio-political support for green hydrogen. Public sentiment towards nuclear power is also among the highest in the Baltic Sea region, suggesting that investments in pink hydrogen are unlikely to be a publicly accepted [27].

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Appendix C

Country profile Sweden

Contents

Summary of national opportunities and challenges

Drivers	**Barriers**
Low-cost, clean electricity	Electricity grid capacity is limited in some areas, and increased production of renewable electricity will be needed to support hydrogen initiatives
Strong political support for decarbonization	Availability of skilled workforce, ability to attract foreign experts especially to northern Sweden
Great potential for building new wind power capacity, especially in northern Sweden	Need for additional foreign investments to refine hydrogen to potentially higher value goods (plastics, e-fuels ammonia, etc.)
Clearly identified potential hydrogen valleys with distinctive characteristics	Backtracking on climate action at political level
Biogenic CO_2 and freshwater availability	Declined community and municipal acceptance on wind power due to lack of compensation and perception of energy injustice, which arises from the unequal distribution of wind power across the country
High-tech society	
Large H2 offtakers: ongoing development for fossil-free steelmaking process	
Socio-political acceptance driven by concerns over climate change and a commitment to decarbonization.	

National hydrogen strategies and targets

The proposal for **National Hydrogen Strategy of Sweden** [1], requested by the **Swedish Government** and developed by the **Swedish Energy Agency**, was published in November 2021. The strategy has not yet been officially adopted. According to the strategy, large fossil-free electricity production potential makes Sweden viable location to produce fossil-free hydrogen and the strategy sees hydrogen as an important element in achieving the Swedish climate goals especially in the industrial sector. In addition to reducing emissions, fossil-free hydrogen and its derivatives are seen to contribute to strengthening the security of supply. The strategy also highlights the system benefits of hydrogen i.e. via stabilizing electricity price fluctuations and the potential of hydrogen to store variable renewable energy. The strategy suggests so assess whether Sweden could also act as a potential net exporter for hydrogen and hydrogen derivates.

The strategy has divided the hydrogen development in Sweden into two phases. During Phase 1 (2022-2030), it foresees that electrolyzers to be mainly installed in existing industries, such as in iron and steel industry, chemical production, and refineries, but new operations in these fields may also be established. Local hydrogen demand sources such as hydrogen refueling stations may also drive the installation of smaller electrolyzer units apart from industries. Due to lack of geological storage sites for hydrogen, large-scale storage sites might be needed outside the country borders. However, lined rock cavern technology for large-scale storage of hydrogen can become an opportunity in Sweden after the technology is more mature.

In the second phase (2031-2045) of the strategy, new value chains for fossil-free hydrogen and its derivatives are being developed and the decarbonization of the industry sector continues. However, this requires that there is sufficient availability of fossil-free electricity and transmission grids. Furthermore, in the second phase, hydrogen has an established role in the transportation sector as well, including e.g., heavy-duty vehicles, work machinery but also shipping and aviation in some extent, which may lead to increased need of electrolyzer capacity.

Hydrogen Strategy /Roadmap
Draft
National Hydrogen Strategy of Sweden (2021)

The **National Hydrogen Strategy of Sweden** proposes two targets for the expansion of electrolyser capacity:

- **5 GW_{el} electrolyzer capacity by 2030**
    - Estimated additional electricity demand of 22-42 TWh
- **15 GW_{el} electrolyzer capacity by 2045**
    - Estimated additional electricity demand 66-126 TWh

Quantified targets for hydrogen production
Yes
•5 GW electrolyzer capacity (2030) •15 GW electrolyzer capacity by (2045)

Prior to the National Hydrogen Strategy of Sweden, Fossil Free Sweden - an initiative of the Swedish Government - also launched a "**Hydrogen strategy for fossil free competitiveness**" in 2021, that has been developed together with companies and other stakeholders across the hydrogen value chain [2]. The strategy suggested prioritized proposals that could foster hydrogen development in Sweden and as an example, proposed a planning goal for the Swedish Government of having 3 GW of installed electrolyzer capacity installed by 2030 at least 8 GW by 2045.

National networks

Hydrogen Research Programme is a programme initated by Energiforsk, which provides a neutral discussion platform between industry, academia, and politics. The programme focuses on, for example, hydrogen's role in the electricity system, technology and cost comparisons for different applications, incentives, and safety and regulation [3].

Västsvenska kemi- och Materialklustret is a cluster that combines the business, academia, and the public sector in Västra Götaland region [4]. The cluster organizes seminars, company meetings, and discussions with decision-makers, while also initiating or participating in innovation and development projects. Additionally, they collaborate with entities outside the Cluster, as well as with other clusters in Sweden and across Europe.

Mid Sweden Hydrogen Valley is a regional partnership formed in 2021 and coordinated by Gävleborg region, which comprises stakeholders from various sectors, including the manufacturing industry, the transport and energy sectors, academia and research institutions, county administrations, and representatives from regional associations in Dalarna and Gävleborg [5].

Hydrogen state-of-play

Sweden is a very industry-intensive country in which fossil hydrogen is also produced, primarily for the refining industry, but also for other uses such as methanol production (Figure 1). Sweden has also electrolytic hydrogen production, which is used, for example, in piloting activities of fossil free steel production and piloting hydrogen storage [6] and for heating steel prior to rolling heat steel before rolling [7].

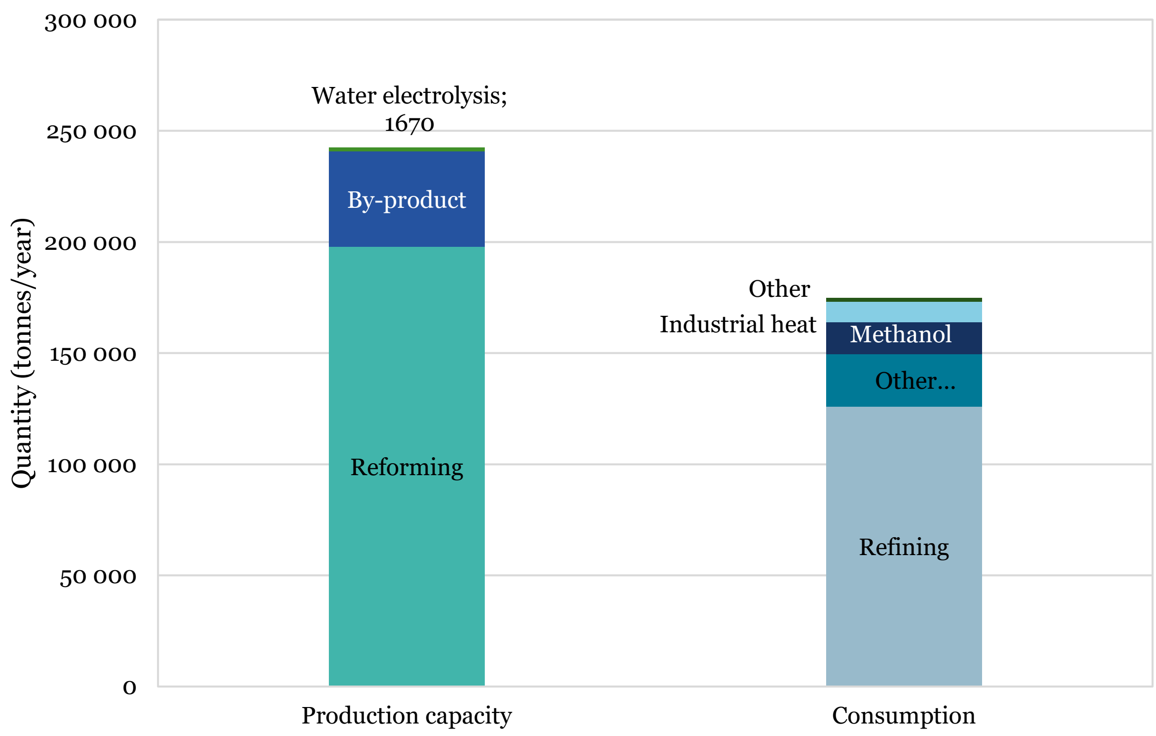

Figure 1. Hydrogen production and consumption in Sweden [8].

The annual dedicated hydrogen production in Sweden is approximately **199 kt/a**, of which 1.67 kt/a is based on water electrolysis (Figure 1). Assuming that 198 kt/a of hydrogen is produced by steam methane reforming (SMR) with emissions of 9 $kgCO_2/kgH_2$, decarbonising Sweden's fossil-based hydrogen production would lead to 1780 kton of CO_2 reduction, which corresponds 3.9 % of Sweden's total CO_2 emissions (total emissions 2022: 45 249 kton CO_2-eq excl. LULUCF [9]). The locations of the operational hydrogen production facilities are presented in Figure 2.

Figure 2. Operational hydrogen production facilities. Facilities with unspecified capacity indicated by triangle markers [10].

Existing hydrogen consumption sources	CO_2 reduction potential in fossil hydrogen production
175 kt/a	**3.9%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [11]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel. [12]

Currently the main sector consuming hydrogen in Sweden is the refining sector. Sweden has four refineries with capacities of 10.5 Mt, 4 Mt, 1.5 Mt and 0.4 Mt of crude oil annually [13] in which fossil hydrogen could be replaced with a clean alternative. In addition, Sweden has two primary steel production sites by SSAB, with annual steel production capacities of 1 700 and 2 200 kt/a [14], in which hydrogen can be used as a decarbonisation pathway. In fact, SSAB has recently revealed plans to build a new fossil-free mini-mill to Luleå, using its HYBRIT technology, based on Direct Reduced Iron (DRI) [15]. In addition, in 2023, SSAB decided to convert its primary steel mill in Oxelösund to fossil-free steel production. Both refining and steelmaking sectors can be important drivers for clean hydrogen market in Sweden and according to the estimates, decarbonisation of the Swedish steel industry will lead to 10% CO_2 emission reductions in Sweden [16]. Locations of these example industrial plants in Sweden with potential for clean hydrogen use in decarbonisation are mapped in Figure 3.

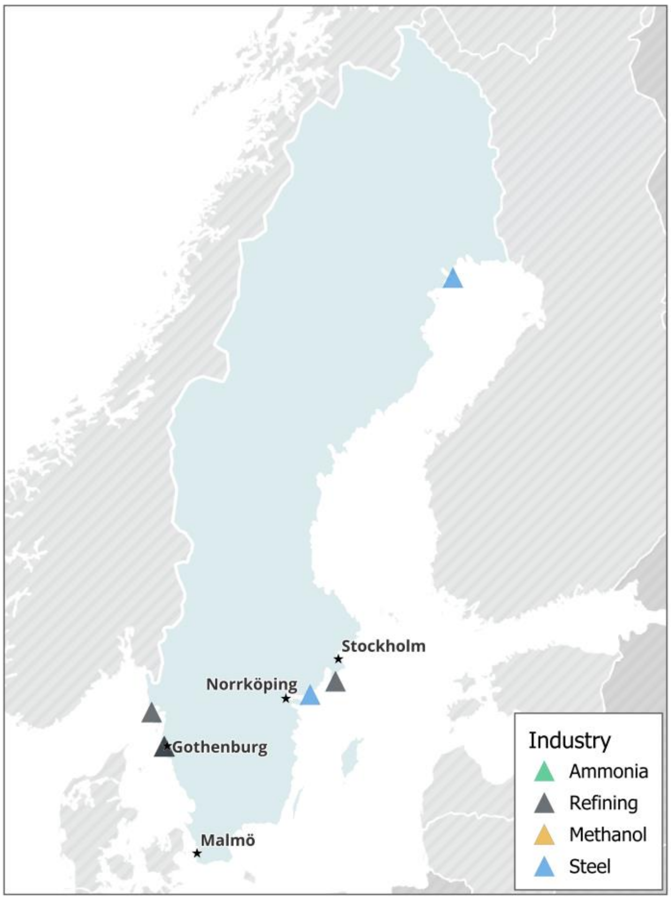

Figure 3. Locations of example industrial plants in Sweden with potential for clean hydrogen use in decarbonisation.

Ammonia production	Refineries	Steel production
No	**16.7 Mt/a (crude oil)**	**3 900 kt/a (steel)**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxes, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

Sweden has the lowest share of fossil fuels in road transport among the countries in the Baltic Sea region (and in the EU). The hydrogen opportunities in the transport sector concern especially long-haul transport and non-road mobile machinery applications. Sweden is an elongated country with long transport distances to and from remote areas, especially in mining, steel, and forestry industry. Mines are an attractive target for hydrogen use as they have large-scale machinery which can operate 24/7, and often have heavy-duty road transport in and out [17].

Heavy duty transport in Sweden allows heavier configurations (60+ tonnes) compared to a maximum configuration mass of around 40 tonnes which is typical in Central Europe. Hydrogen integration to heavy configurations is not a challenge payload-wise since hydrogen is lightweight and the volume of storing hydrogen is not an issue. The direct electrification of long-haul applications would require a large battery system which would result in a portion of the payload to be lost in terms of mass. In addition, hydrogen fuelling is relatively fast compared to charging a large battery and allows a long range with a relatively short stop. The rail network in Sweden is largely electrified, with only 5% share of fossil fuels from the total energy consumption. If electrification proves challenging, hydrogen can be a viable option to replace the diesel locomotives on the few unelectrified connections.

The energy consumption of domestic navigation in Sweden was 144 ktoe in 2022, of which 95% was from fossil fuels [18]. The shipping industry's roadmap for fossil-free competitiveness by Fossilfritt Sverige [19] aims to achieve no net greenhouse gas emissions from domestic shipping by 2045. The ports of Trelleborg, Gothenburg, and Gävle plan to establish hydrogen production to combat high emission levels from current fuels. Green hydrogen will initially power transportation within and around the ports, including vehicles and forklift trucks. In the future, trains, boats, and ships may also utilize hydrogen fuel. In March 2024, Port of Gothenburg carried out emission free excavation work, where hydrogen was used to power an on-site clean hydrogen generator for electricity generation, which supplied energy to an electric excavator involved in a major infrastructure project [20].

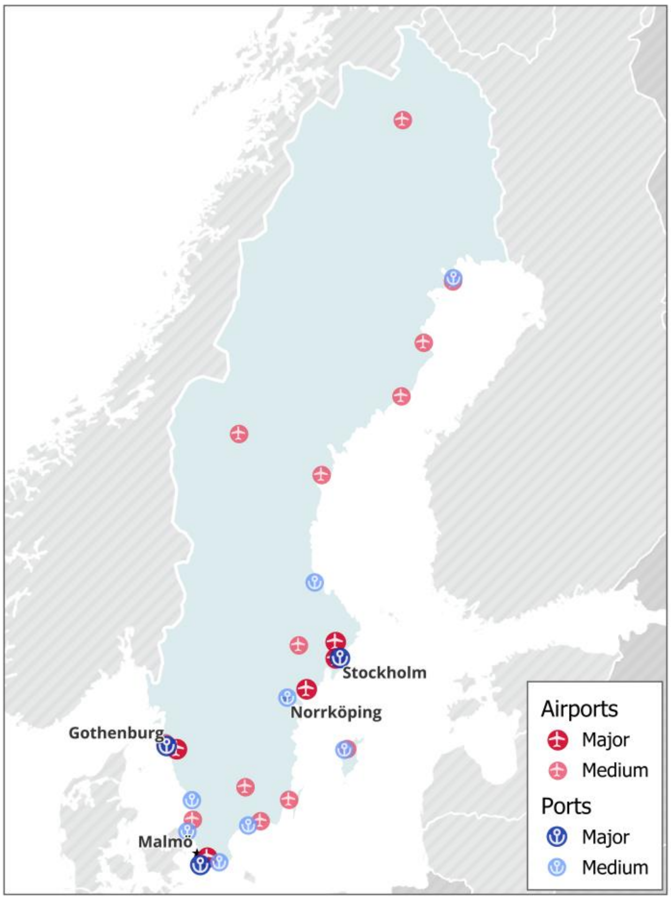

Figure 4. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million).

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
71%	**5% (13 ktoe)**	**144 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [18]

Hydrogen refueling infrastructure

Currently there are five hydrogen refuelling stations in operation in Sweden that are located in Göteborg, Mariestad, Stockholm, Sandviken and Umeå (Figure 5). The hydrogen refuelling station network is expected to grow significantly and Vätgas Sverige estimates that around 100 hydrogen refuelling station will be built around Sweden in the upcoming years [21]. There are several refuelling stations planned at least by Everfuel, Hynion and Hydri AB.

Several of the refuelling stations by Everfuel are built as part of an EU-co-funded Nordic Hydrogen Corridor project which also includes Statkraft, Toyota, Hyundai, and Hydrogen Sweden in the consortium. Everfuel also plans to build stations in Denmark and Norway with the ambition of establishing a Scandinavia fuelling network with 40-50 public hydrogen refuelling stations [22]. The aim is that a third of Scandinavia's population will not need to travel more than 15 kilometers to the nearest hydrogen station, as long as they live along the designated corridor. The planned stations will offer hydrogen refuelling to both passenger and heavy- vehicles.

Vireon AS, a subsidiary Norwegian Hydrogen, is planning to build a hydrogen refueling corridor from Northern Finland via Sweden and Denmark to the continental Europe. The company has recently (4/2024) received funding to build a total of seven hydrogen stations to Finland and Denmark [23] and is also expanding its refueling network in Norway.

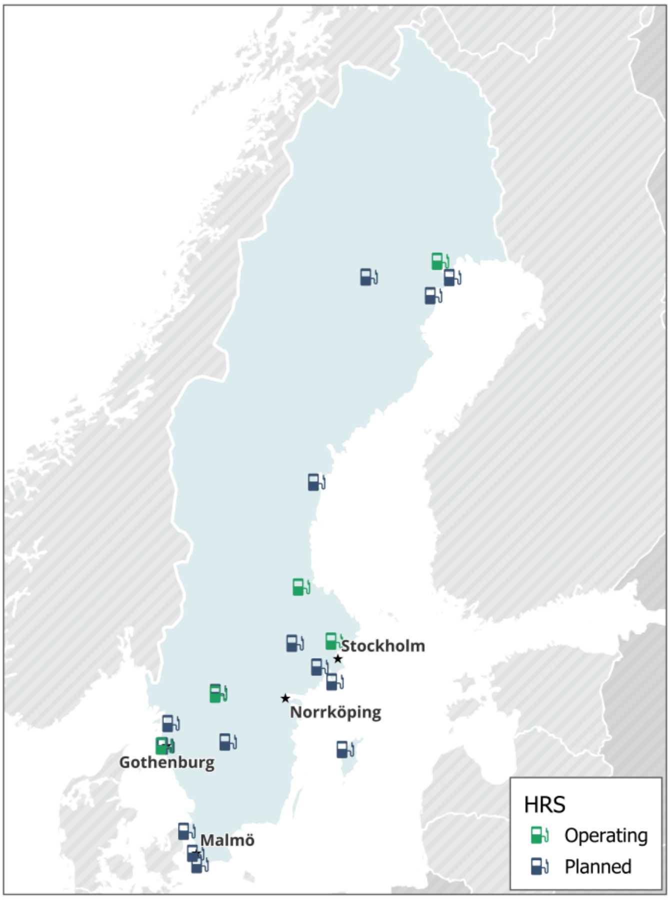

Figure 5. Operating and planned hydrogen refueling stations [24], [25].

Resource availability

Renewable electricity production

Sweden's abundant renewable energy resources provide a strong foundation for large-scale hydrogen production. Sweden's electricity production today is based on 41% hydropower, 29% nuclear, 19% wind power, 10% thermal and 1% solar [26]. National energy target was updated in 2023 to 100% fossil-free electricity production by 2040. Sweden has four electricity price zones, out of which two zones in the north of Sweden have more than 90% renewable electricity [27]. Therefore, these zones are ideal for renewable hydrogen production according to the EU RFNBO delegated act. The other two zones qualify the criteria for low-greenhouse gas intensity of less than 18 g CO_2-eq/MJ.

Sweden is also a major electricity exporter in the EU. However, the anticipated increased electricity demand for hydrogen production in Sweden will limit the share of electricity that can be exported. In addition, new power generation capacity will be required to produce the great need of electricity for industrial clean hydrogen investments that are planned, especially in the north but also in other regions. One important barrier to the development of renewable energy in Sweden is the limited power grid availability.

The recent trends in renewable electricity generation capacity in Sweden are illustrated in Figure 6. Wind power has experienced significant growth in Sweden in recent years, with the country investing in both onshore and offshore wind farms. Wind power contributes around 15-20% of Sweden's electricity generation, depending on factors such as wind conditions and capacity expansion.

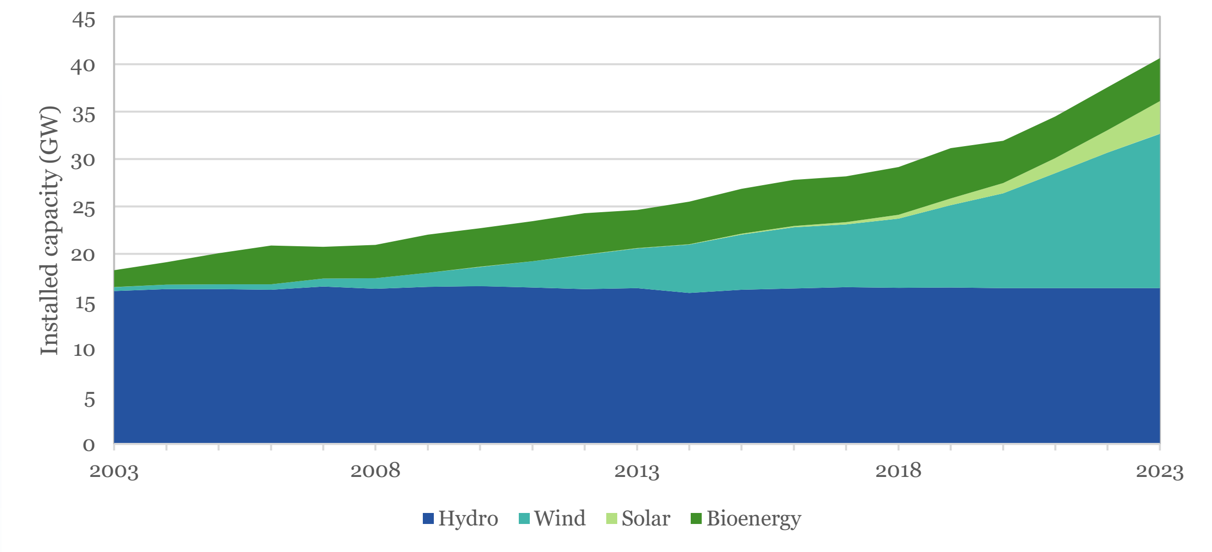

Figure 6. Renewable electricity generation capacity in Sweden between 2003-2022 [28].

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. For Sweden, these projects include 5.1 GW of onshore wind energy, and 115.1 GW of offshore wind energy, totalling **120 GW** of new renewable electricity capacity in the pipeline (Figure 7), with vast majority of the projects being offshore wind energy projects.

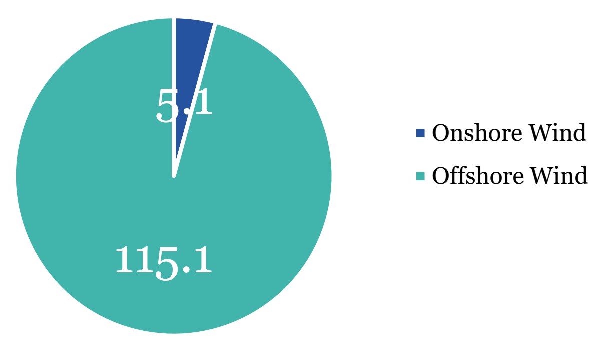

Figure 7. Renewable electricity projects (GW) in pipeline in Sweden based on data collection conducted in BalticSeaH2.

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 8 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

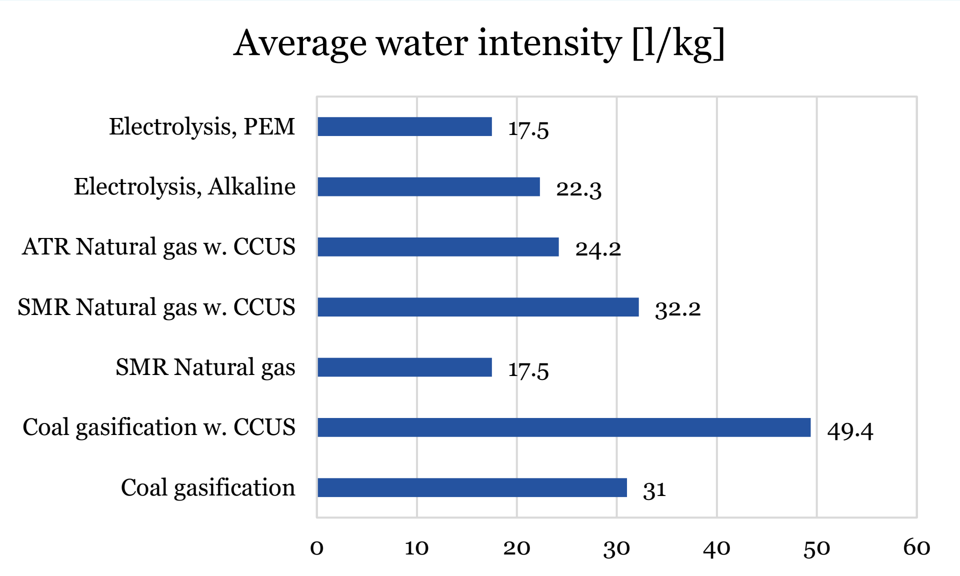

Figure 8. Average water consumption intensities by hydrogen technology [29]

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

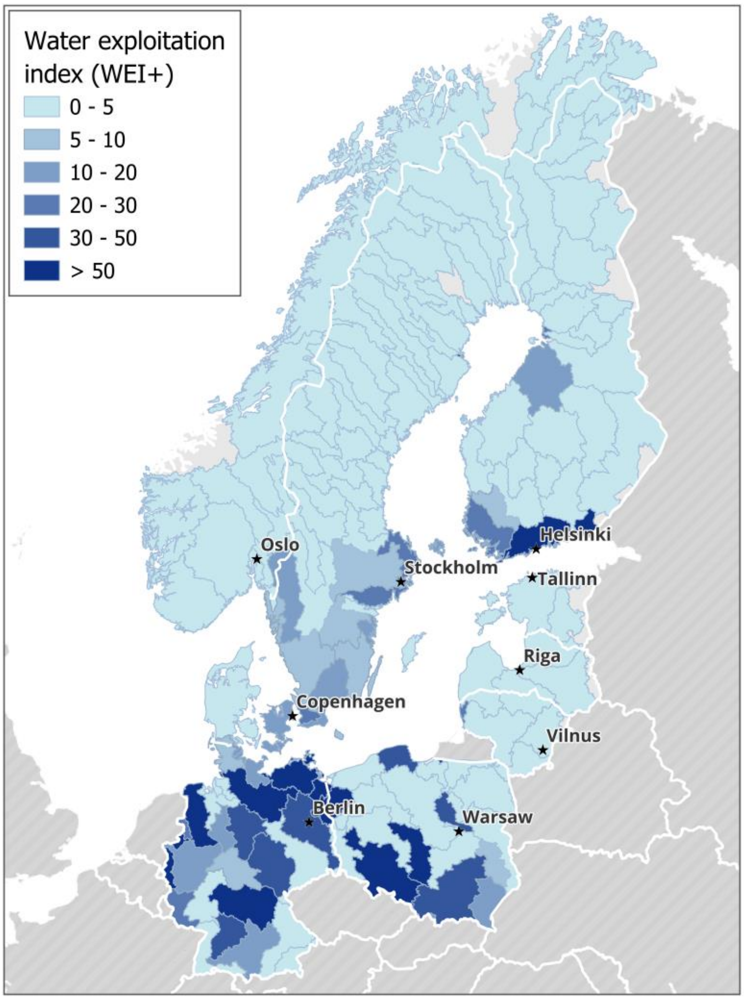

Figure 9. Regional WEI+ values for BSH2 countries in Q3, 2019 [30].

The local water stress conditions determine that 91% of the hydrogen projects that are operating or planned in Sweden are in areas with low water stress, 3% are in areas with low to medium water stress, and 3% are in areas with medium to high water stress [29]. The expected hydrogen projects involving water electrolysis would raise hydrogen production in Sweden by 1 100 kt/a, which means an extra 22 million m^3 of water use (assuming average use of 19,9 l/kg between PEM and AEL). In general, Sweden does not face water scarcity and its yearly WEI+ is 0.22%. However, yearly calculations of the WEI+ at the national level do not account for uneven spatial and seasonal distribution of resources and may therefore hide water stress that occurs on a seasonal or regional basis.

WEI+
0.22%
BSR range: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (< 0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Annual CO2 emissions of Sweden are 50 Mt/year (when calculating industrial sources larger than 0,1 Mt/year), consisting of 33 Mt/year of biogenic and 17 Mt/year of fossil CO2. The CO2 sources are mainly concentrated near the coastal areas, as well as Southern Sweden in general (*Figure 10*). As Sweden has a strong forestry sector and thus, most its CO2 emissions are of biogenic origin, there is good potential for power-to-x applications. If needed, the northern CO2 point sources could possibly be collected e.g., via a pipeline, as most of them are nicely lined up. Also, in the southern part of Sweden, there are good possibilities for CO2 hubs, as there are many point sources relatively close to each other.

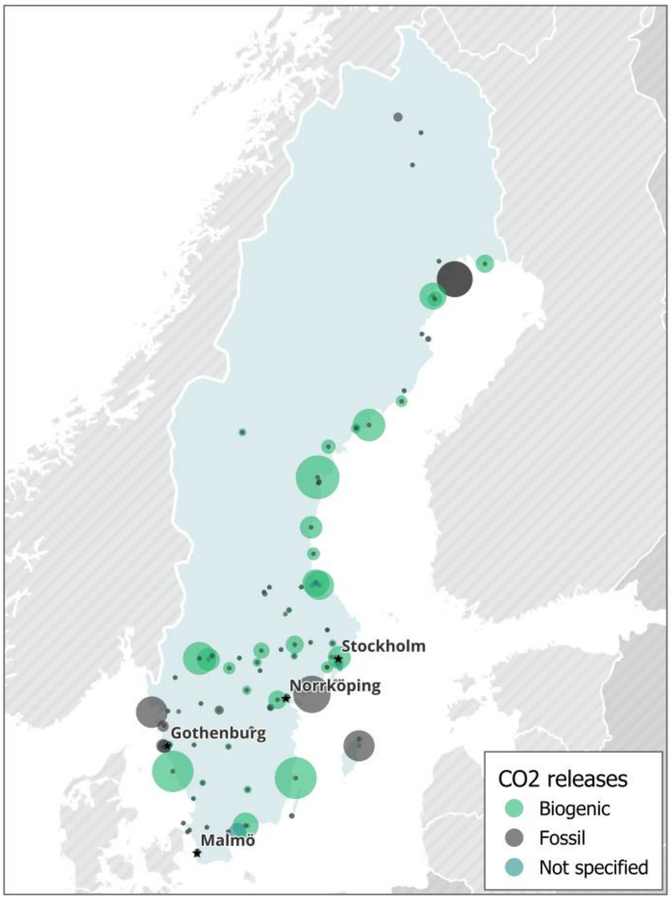

Figure 10. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [31].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

Sweden has a natural gas transmission pipeline of roughly 600 km in the southwest region, which is interlinked with Denmark [32]. The proposed hydrogen transmission infrastructure will be newly built without incorporating any existing pipelines that have been repurposed for hydrogen transport. The construction of hydrogen transmission infrastructure will begin with regional coastal networks in the southwest, central-east, and north of the country. By 2040, these networks are envisioned to be linked together to form a national hydrogen transmission system [33].

Two cross-border hydrogen infrastructure development projects are currently ongoing together with Swedish and Finnish gas transmission system operations Nordion Energi and Gasgrid Finland: 1) Nordic Hydrogen Route, designed for cross-border hydrogen transmission in the Bothnia Bay Region and 2) Baltic Sea Collector, which plans for an offshore hydrogen pipeline connecting Finland, Sweden and Germany. Both of these pipelines are scheduled to become operational by 2030 [34].

- **Nordic Hydrogen Route** – Bothnian Bay is Nordion Energi's and Gasgrid Finland's joint project to accelerate hydrogen economy by developing cross-border hydrogen transmission pipeline infrastructure and open hydrogen market between Sweden and Finland around the Bothnian Bay. The goal of the project is to enhance achievement of carbon neutrality targets, support regional green industrialization, economic development, and European energy self-sufficiency.

- In **Baltic Sea Hydrogen Collector** project, the opportunity to build offshore hydrogen transmission pipeline infrastructure connecting Sweden, Finland and Central Europe to enable clean hydrogen production for Europe's demand is studied. The project partners are Nordion Energi, Gasgrid Finland and industrial companies OX2 and Copenhagen Infrastructure Partners.

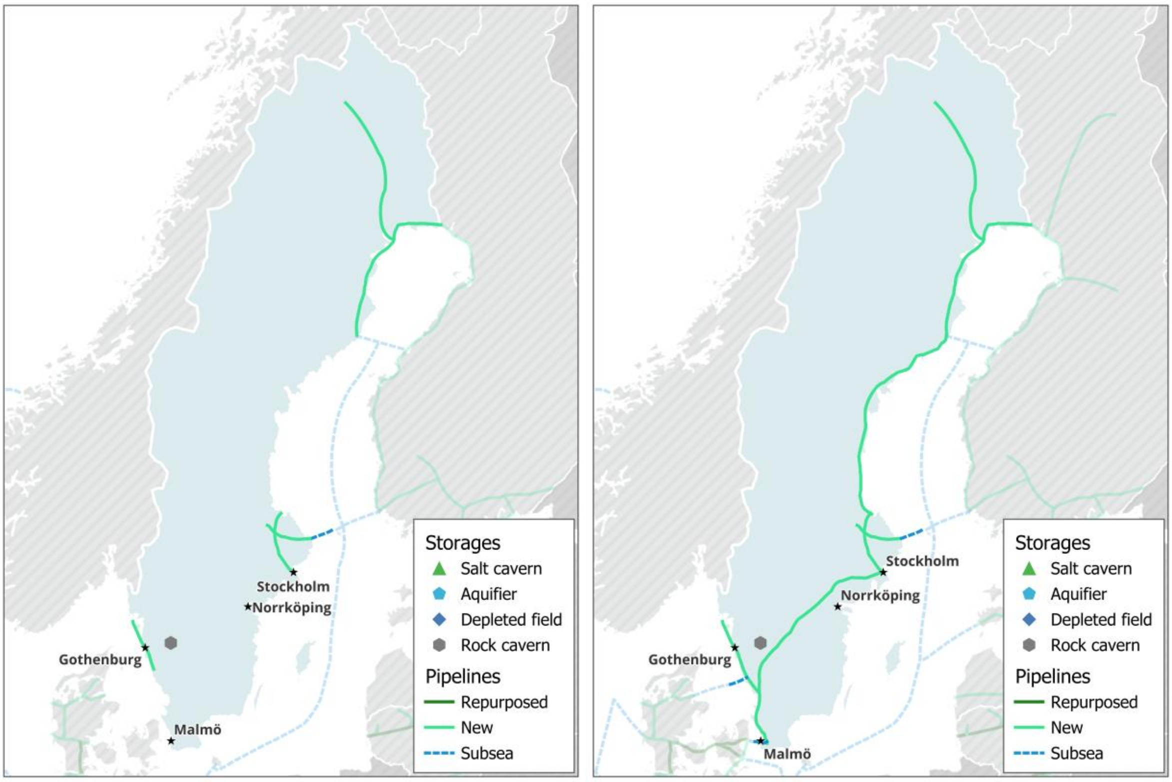

Figure 11. Left: A European hydrogen infrastructure vision for 2030. Right: vision for 2040 [35].

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [36]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which only salt cavern has reached industrial maturity in storing pure hydrogen. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

Sweden has a unique advantage in large-scale hydrogen storage: it developed lined rock cavern (LRC) technology for underground gas storing, since it lacks salt deposits. The technology was proven to be suitable for natural gas storing by decades of operational experience, and a 100 m^3 hydrogen storage facility was built in Luleå and launched by HYBRIT in 2022. The storage was tested on the electricity market and showed that it could operate flexibly and reduce the hydrogen production cost by up to 40% during the month-long test. The national expertise in LRC technology gives Sweden a good opportunity to also export knowledge to areas where salt caverns are not an option.

Sweden has a large hydropower capacity, which makes the energy system better adapted than most BSH2 countries to balance the variability that increasing weather-dependent renewable electricity causes. However, significant hydrogen use is expected in the Swedish industrial sector, for which large-scale hydrogen storage can help to lower the cost and ensure the reliability of hydrogen supply.

Hydrogen production plans

As of today, Sweden has three operational electrolytic hydrogen production units. In HYBRIT pilot by SSAB, LKAB and Vattenfall, electrolytic hydrogen is used in the piloting activities of fossil free steel production and hydrogen storage in Luleå. Ovako uses electrolytic hydrogen produced with 20 MW electrolyzer to heat steel before rolling and in Oskarshamn Nuclear Power Plant, electrolytic hydrogen has been produced from nuclear power since 1992 to cool down large generators with excess being sold to market [37].

Based on data collection, many hydrogen projects in varying degrees of maturity are in development, with a total estimated electrolyzer capacity of over **4.5 GW**. It is worth noting that many of the projects in early stages have not disclosed any information regarding their planned production capacities or volumes and are hence excluded from this value.

While not all projects have disclosed their individual capacities, they may have provided estimates of the annual hydrogen production volumes (kt/a). Assuming a 65% electrolyzer efficiency and year-round operational availability for projects that have only provided information of the expected electrolyzer capacity (MW), the combined hydrogen production volume in Sweden would be above **1 100 kt/a** by 2030. A small fraction of this volume (1 %) is planned to be generated from plasma gasification of waste [38], while rest is electrolytic hydrogen. The current hydrogen production capacity in Sweden is approximately 242 kt/a [10], indicating that if all currently planned projects were to be realized, Swedish hydrogen production capacity would increase more than fourfold.

In the Figure 12 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project. As can be seen, the projects are primarily situated along the coastal regions of Sweden.

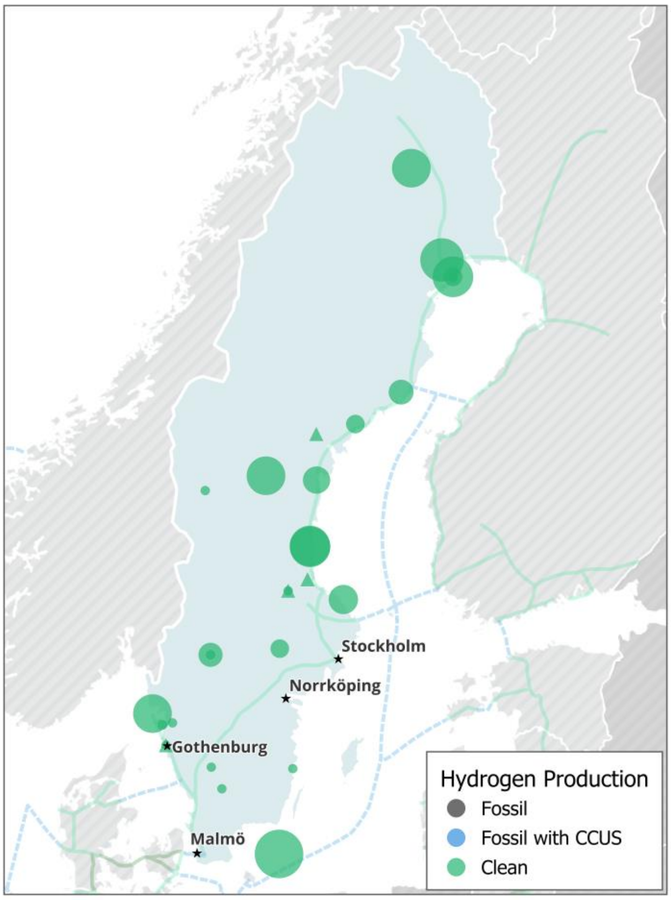

Figure 12. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

Based on public announcements, the following large-scale clean hydrogen production projects have received final investment decision or are currently being constructed in Sweden:

- Companies **SSAB, LKAB, and Vattenfall** are currently building a demonstration plant in Gällivare for producing fossil-free sponge iron at an industrial scale [39]. This plant will have a **500 MW** electrolyzer capacity.
- **H2 Green Steel** is building a green steel plant in Boden with an **800 MW** electrolyzer capacity [40].
- FlagshipONE, an e-methanol project by **Liquid Wind & Ørsted**, is currently under construction in Önsköldsvik with a **70 MW** electrolyzer capacity [41].

The cumulative capacity of clean hydrogen production projects in Sweden is presented in Figure 13. Note that several large projects in early conceptual stages have not stated the planned commissioning year. In this case, the project is expected to be operational in 2030 or beyond. Additionally, projects without specified capacity or annual production have been excluded from the graph. Despite the exclusions, the trajectory is clear: the hydrogen capacity in Sweden would increase drastically in the upcoming years. High production capacity in 2030 and later shows that many of the projects are still in initial phases and have not indicated the planned start-up year yet.

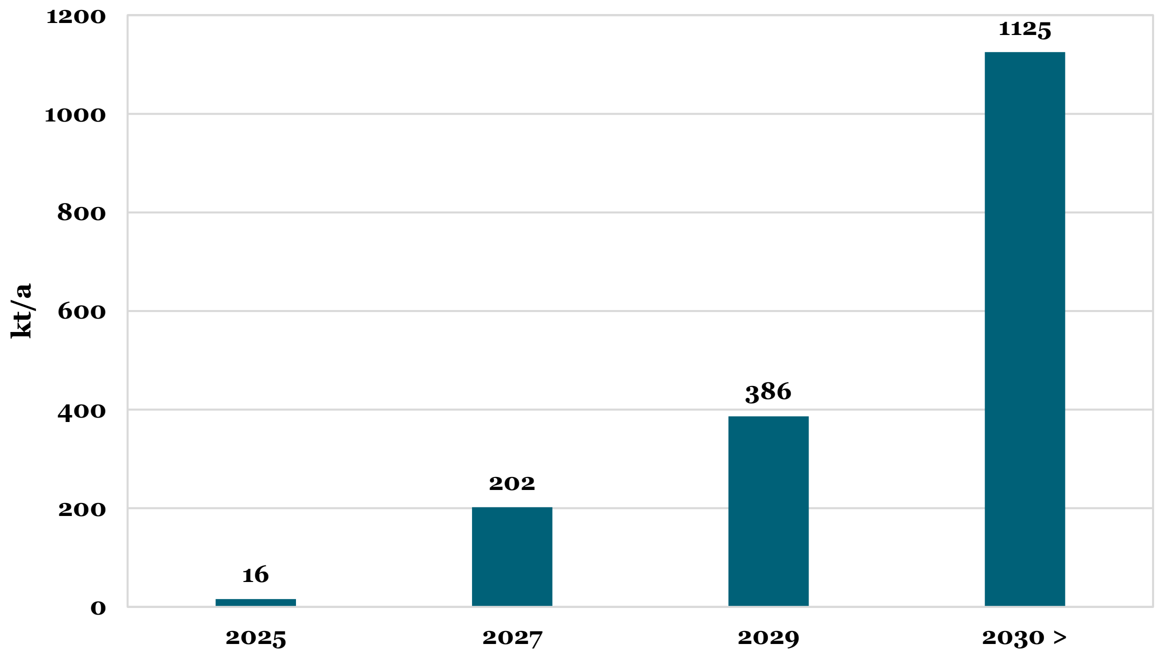

Figure 13. Cumulative capacity of clean hydrogen production projects in Sweden based on data collection conducted within BalticSeaH2.

Potential geographical areas for hydrogen development

The potential for both hydrogen production and usage vary throughout the Sweden and already today some geographical trends and differences in hydrogen usage is notable. These regions can be summarized as the main "Hydrogen Valley's" with different industry drivers that are active in these regions. These are highlighted in the map below (Figure 14) and divided through the country electricity price areas.

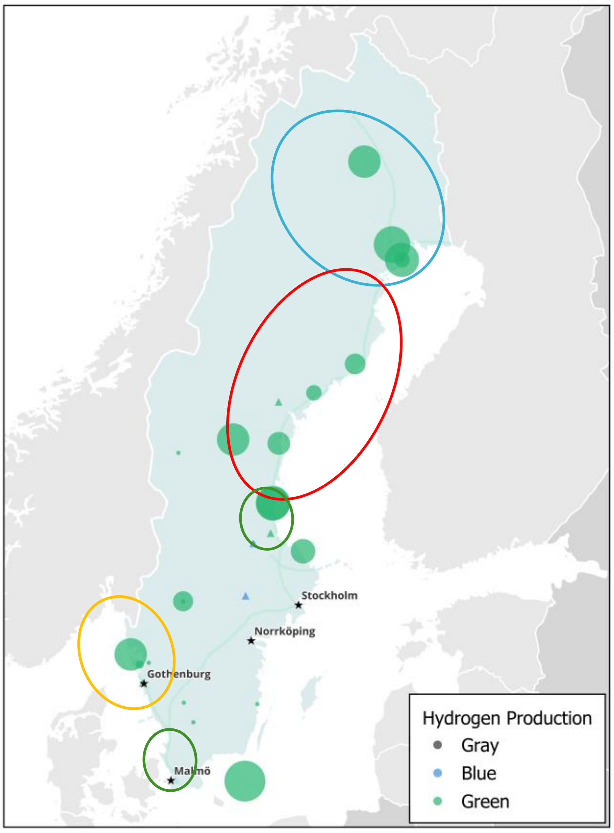

Figure 14. Potential geographical areas for hydrogen development in Sweden.

Northern Sweden (SE1) (blue area): Major investments in hydrogen infrastructure and usage are taking place in Northern Sweden by several industries such as Hybrit, H2Green Steel and Northvolt. According to current projections, the iron and steel industry in SE1 area will make up of approximately 10 GW of hydrogen (80 TWh) by 2050.

East/Mid Sweden Hydrogen Valley (SE2) (red area): Mid Sweden Hydrogen Valley has been running for several years. Around 40 companies with an interest in hydrogen are linked to the cluster. The East/Mid Sweden is an industry-heavy region and many transport routes and modes of transport pass through it. Several companies in the region are leading the way for hydrogen transformation, namely Ovako, Maserfrakt, DalaVind and Svea Vind Offshore. The announced hydrogen production projects in the region are already at GW-scale.

West Sweden: Chemical and Materials Cluster (SE3) (yellow area): The project "Regional Collaboration on Hydrogen" has just ended in the region. The region is the largest user of hydrogen in Sweden at the moment (about 90%). In addition, Gothenburg and Stenungsund and have long and extensive experience of using hydrogen. According to current projections the refineries and chemistry industry in SE3 price area will make up of approximately 2,6 GW hydrogen by 2045.

In addition to these regions, more hydrogen initiatives are announced in **SE3 and in SE4 areas (green area).** As an example, Ovako has 20MW of hydrogen production in Hofors in SE3 and Högnäs AB in SE4 have plans for 16 MW hydrogen production to replace fossil-based hydrogen. Furthermore, the port of Trelleborg have planes in using hydrogen in their machine park and at Gotland, the shipowner Gotlandsbolaget has announced ambitious plan for two hydrogen powered ships by 2027 and 2035.

Education and employment

Vätgas Sverige tracks the educational offer related to hydrogen in Sweden. The universities that currently provide education that supports hydrogen economy development in Sweden are Luleå University of Technology, Chalmers university of technology, KTH, Dalarna University, Lund University, Mälardalen University, Uppsala University.

RISE Research Institute of Sweden offers courses on Hydrogen safety and hydrogen in heavy transport targeting adult learners [42].

University of Applied Sciences in Trelleborg offers hydrogen education package, which comprises 60 higher vocational education credits and gives competence to work in, for example, risk investigations and analyses, permit assessments for and planning of hydrogen plants.

Lapplands Kommunalförbund starts a Higher Vocational Education programme on hydrogen in autumn 2024, which aims to educate workforce to work in the industrial and energy industry as an operation and maintenance technician, process technician and process operator. The training also includes safety training that the industries demand.

YH Akademin provides higher vocational education programme on green hydrogen applications and development, consisting of 60 higher vocational education credits.

In general, there is lack of workforce all over the country in technical fields in Sweden. The need for skilled workers is particularly pressing in Northern Sweden, where large hydrogen production investments are taking place. More competence is needed through the whole hydrogen value chain.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [43]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [44]. Recent survey [45] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [46]. The rise of right-wing politics and growing "greenlash" against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [47].

Another barrier potential barrier stems from a community-rejection (also referred to as the NIMBY-effect, “Not In My Backyard”), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [45], [48], [49], [50], [51]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [52].

The success of this community ownership model in driving Denmark’s wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [45], [46] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

In the Swedish context, there remains little research on the socio-political and community acceptance of hydrogen technologies. However, growing amount of literature on wind power acceptance suggests that mitigating conflicts related to wind power can become a key factor in the successful deployment of hydrogen economy in Sweden. Swedish municipalities have a unique position to veto large-scale wind power projects, and 78% of all wind farm constructions were blocked by municipalities in 2021 [53]. Although popular amongst the Swedish public [43], research suggests perceptions of injustices (i.e. insufficient economic, social and environmental benefits to local communities) has fuelled local opposition [48], [54]. Given the opposition and the position of municipalities in driving and blocking energy initiatives, it is essential to collaborative with the municipalities to ensure a successful and socially accepted hydrogen transition.

In a recent survey, the Swedish public (and other Nordic countries as well) was also among the least convinced of the safety and sustainability of hydrogen, compared to other EU Member States [45]. This suggests an increased need for awareness-raising on safety-aspects and sustainability of green hydrogen.

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Appendix D

Country profile Norway

Contents

Summary of national opportunities and challenges

Opportunities	Challenges
Clean electricity grid	Low demand - hydrogen projects structured to integrate into existing production or sold to specific vessels rather than directed to open market
Clear need for decarbonization in maritime sector with little alternatives other than hydrogen and hydrogen derivatives	No existing hydrogen infrastructure
Access to natural gas – potential for blue hydrogen production and CO2 management	Lack of skilled workforce
Multiple potential hydrogen valleys identified – some have reached financial investment decisions	Local opposition on wind power projects
Domestic electrolyzer manufacturing competences	
Great willingness to invest in green initiatives	
Socio-political acceptance driven by concerns over climate change and a commitment to decarbonization.	

National hydrogen strategies and targets

The Norwegian Government's hydrogen strategy [1] was published in 2020 by Norwegian Ministry of Petroleum and Energy and Norwegian Ministry of Climate and Environment. The strategy highlights that the Government wants to prioritize the areas in the hydrogen value chain, in which Norway has a particular advantage. **Heavy industry, maritime transportation and heavy traffic** are seen as the most promising sectors suitable for hydrogen applications as these are sectors with fewer or no zero emission alternatives. Contrary, hydrogen as an energy storage for variable renewable energy is not seen as important in Norway due to robust and flexible hydropower supply.

The strategy states that conditions for hydrogen in Norway are ideal due to several factors. These include for instance many years of industrial experience across the hydrogen value chain but also in processing gas through the petroleum industry. In addition, availability of large gas reserves and ability increase renewable energy capacity and the potential of continental shelf in acting as a CO2 storage for hydrogen production via natural gas and carbon capture and storage (CCS) are seen as an important driver for hydrogen. Norway also covers large segments of the maritime value chain in which hydrogen could play in important role.

An important objective for the Government is to increase the number of pilot and demonstration projects in Norway and hence aid the technology development and commercialization. In addition, the Government aims to advance the development of carbon capture, transport and storage technologies to enable cost-effective and full-scale CCS plants in Norway to produce clean hydrogen from natural gas. As an example of a support measure in transportation, the Government aims to foster emission-free transportation by allowing hydrogen vehicles the same tax breaks as those of battery electric vehicles until 2025 or 50,000 vehicles.

Hydrogen Strategy/ Roadmap
Yes
The Norwegian Government's hydrogen strategy (2020)

As a follow-up for the hydrogen strategy, the Government published a **Hydrogen roadmap** in June 2021 [2]. The roadmap sets the ambition to have hydrogen established as a realistic alternative in the maritime sector by 2030 and to have an established market for the production and consumption of hydrogen by 2050. In short-term, the targets of the Government are to:

- Establish **five hydrogen hubs for maritime transport** by 2025
- Establish **one or two industrial projects** with associated production facilities
- Establish **five to ten pilot projects** for the development and demonstration of new, more cost-effective hydrogen solutions and technologies

Quantified targets for hydrogen production
No
Main indicators: • 1-2 industrial projects with associated hydrogen production facilities by 2025

National hydrogen networks

Hydrogen has over the last years received significantly increased focus from the authorities and the industry, and several projects and initiatives have been initiated throughout Norway. There are about 15 clusters in Norway involved in different hydrogen initiatives. **H2 Cluster** has initiated a forum for the most forward leaning of these clusters. There are also lots of industry initiatives on the green hydrogen projects.

The County Network is a cooperation between counties and municipalities in Norway with the goal to develop well-functioning value chains for hydrogen throughout the country. The County Network aims to increase the competence about hydrogen, provide input to regional and local action plans and strategies, act as a discussion partner in preparation of input for public consultations, work for improved national framework conditions that are of particular importance to municipalities and counties and increase the cooperation between the participants by sharing experiences and coordinating activities.

Hydrogen state-of-play

Norway has been producing hydrogen in relatively large scale since the start of Norsk Hydro's production facility at Rjukan in 1929 and in Glomfjord 1949. The water electrolysis factory in Glomfjord was in fact the world largest at a time with daily production capacity of above 65 tons hydrogen for the purpose of fertilizer production. As natural gas became available at a lower cost, production switched to using natural gas as raw material. Hence, hydrogen production in Norway is currently primarily based on natural gas (Figure 1). Primary applications for hydrogen in Norway are ammonia and methanol production and oil refining.

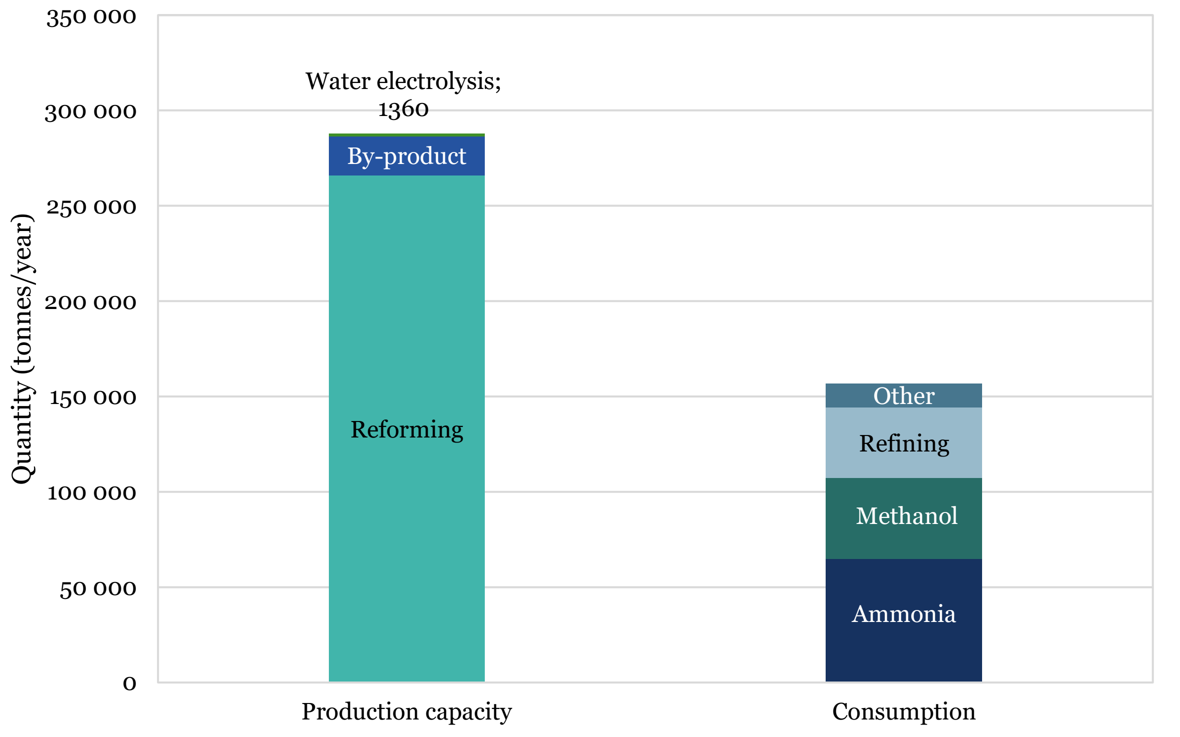

Figure 1. Hydrogen production and consumption in Norway [3].

The annual dedicated hydrogen production in Norway is approximately **267 400 t/a**, of which 1 360 t/a comes from water electrolysis (Figure 1). Assuming that 266 kt/a of hydrogen is produced by steam methane reforming (SMR) with emissions of 9 kgCO2/kgH2, decarbonising Norway's fossil-based hydrogen production would lead to 2394 kt of CO2 reduction, which corresponds 4.9 % of Norway's total CO2 emissions (total emissions 2021: 48 900 kt CO2-eq excl. LULUCF [4]). The location of the operational hydrogen production facilities is presented in Figure 2.

Figure 2. Operational hydrogen production facilities. Facilities with unspecified capacity indicated by triangle markers [5].

Existing hydrogen consumption sources	CO_2 reduction potential in fossil hydrogen production
157 kt/a	**4.9%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [6]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel [7].

Currently the main sectors utilising hydrogen in Norway are the ammonia, methanol, and refining sectors. Norway has one ammonia production plant by Yara with annual hydrogen consumption of 64 kt [8] (2022). In fact, the company is currently building a 24 MW electrolyzer unit for clean hydrogen production [9]. The Europe's largest methanol plant is also located in Norway, with over 900 kt/a of annual methanol production. Norway has also an oil refinery with capacity of 10.2 Mt of crude oil annually [10]. As the substitution of fossil hydrogen to clean hydrogen is possible in these sectors, decarbonising these sectors can act as low hanging fruit opportunities to foster the clean hydrogen transition in Norway. Locations of these example industrial plants with potential for clean hydrogen use in decarbonisation are mapped in Figure 3.

Figure 3. Locations of example industrial plants in Norway with potential for clean hydrogen use in decarbonisation.

Ammonia production	Refineries	Methanol production
64 kt/a (hydrogen)	**10.2 Mt/a (crude oil)**	**900 kt/a (methanol)**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 0–900 kt/a (methanol)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxes, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

There is a special potential for hydrogen in transport sector in Norway. The Norwegian Government has, through its work on the Green Industrial Initiative, identified maritime as one of the main priority areas where future hydrogen demand is expected to be large and can provide significant opportunities for sustainable production and value creation in Norway. Comparison between the Baltic Sea region countries on the energy demand of domestic navigation supports this; Norway's demand is the highest.

There is an ambition of the Norwegian Hydrogen Roadmap presented June 2021 to establish five hydrogen hubs for maritime transport within 2025. To support this, Enova, through its program Hydrogen to Maritime Transport in 2022, identified and funded 5 key areas for hydrogen production. Those were Glomfjord in Norland County, Rørvik and Hitra in Trøndelag county, Florø in Vestland county and Kristiansand in Agder county. The five "hub projects" had a deadline to make FID by 31 January 2024, of which Glomfjord and Adger reached FID in January 2024. New programmes will be introduced in 2024.

Regarding rail transport, while most of the railways are electrified in Norway, still more than 1000 km of railways are non-electrified. A report published in 2019 by SINTEF concludes that hydrogen is the most relevant solution in the decarbonisation of non-electrified railway sections from 2030 onwards. [11]

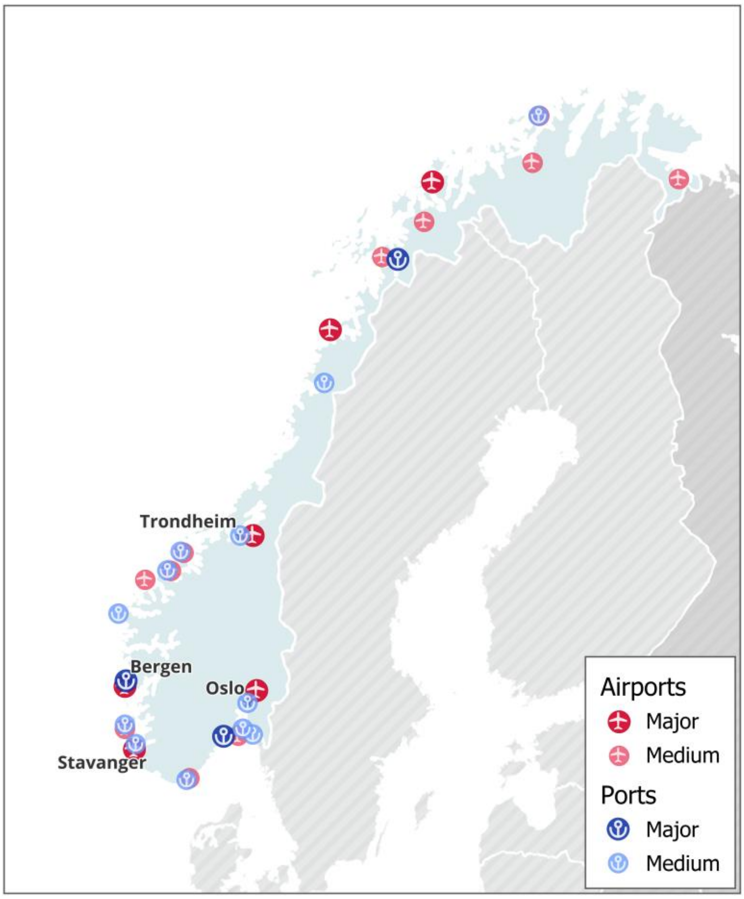

Figure 4. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) [12].

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
84%	**21% (17 ktoe)**	**1 280 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [13]

Hydrogen refueling infrastructure

There are both operational and planned hydrogen refueling stations in Norway (Figure 5), mainly by Vireon AS, a subsidiary Norwegian Hydrogen, Everfuel, Hynion and ASKO. Since 2017, the Norwegian wholesaler ASKO has been using hydrogen to fuel its forklifts and other company vehicles at its distribution center [14]. The hydrogen is produced using solar panels installed on the center's roof. In 2020, ASKO took a step further by introducing four hydrogen-powered trucks manufactured by Scania to pilot hydrogen-based transportation as an alternative for the company's zero-emission distribution goals, mainly by Vireon AS, a subsidiary Norwegian Hydrogen, Everfuel, Hynion and ASKO. Since 2017, the Norwegian wholesaler ASKO has been using hydrogen to fuel its forklifts and other company vehicles at its distribution center [14]. The hydrogen is produced using solar panels installed on the center's roof. In 2020, ASKO took a step further by introducing four hydrogen-powered trucks manufactured by Scania to pilot hydrogen-based transportation as an alternative for the company's zero-emission distribution goals.

Vireon is aiming to build hydrogen refueling corridors across the Nordic region and has received funding from the from Norwegian Government Agency Enova to construct four refueling stations to Norway, namely to Vestby, Stavanger, Dombås and Innlandsporten [15]. These refueling stations pave the way for building Norway's first hydrogen corridor for heavy-duty transport, which will be located between Oslo and Trondheim. The company is also constructing a hydrogen refueling station independently to Hellesylt.

In addition, Everfuel plans to build hydrogen refueling stations in Norway, Denmark and Sweden with the ambition of establishing a Scandinavia refueling network with 40-50 public hydrogen refueling stations [16]. The aim is that a third of Scandinavia's population will not need to travel more than 15 kilometers to the nearest hydrogen station, as long as they live along the designated corridor. The planned stations will offer hydrogen refueling to both heavy-duty and passenger vehicles.

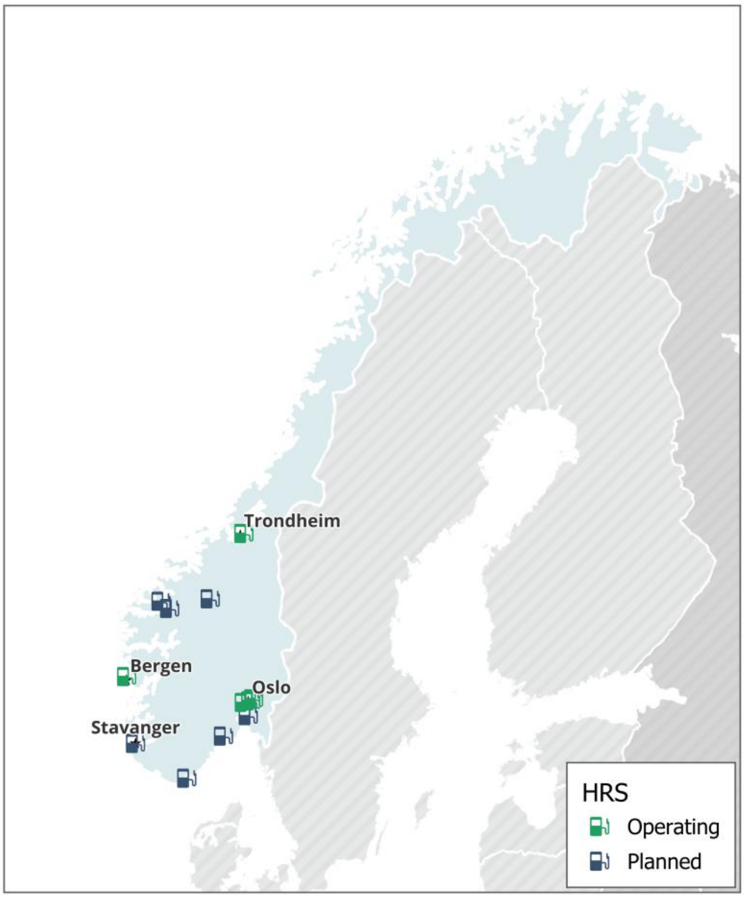

Figure 5. Operating and planned hydrogen refueling stations based on *[17], [18]* and publicly announced projects.

Resource availability

Renewable electricity production

Nearly all of Norway's electricity production is based on renewable energy sources, namely hydropower (almost 90% of production), with geothermal (2%) and wind (10%) providing the rest. While hydropower capacity will be maintained, there is significant growth potential in offshore wind. The government aims to designate regions for 30 GW of offshore wind production on the Norwegian continental shelf by 2040 [19]. However, much of the new offshore capacity will be directed to the decarbonization and electrification of oil and gas fields as part of the government's policy for CO2-management. Therefore, the development of large-scale hydrogen production could be hampered by these priorities. The recent trends in renewable power generation capacity in Norway are illustrated in Figure 6.

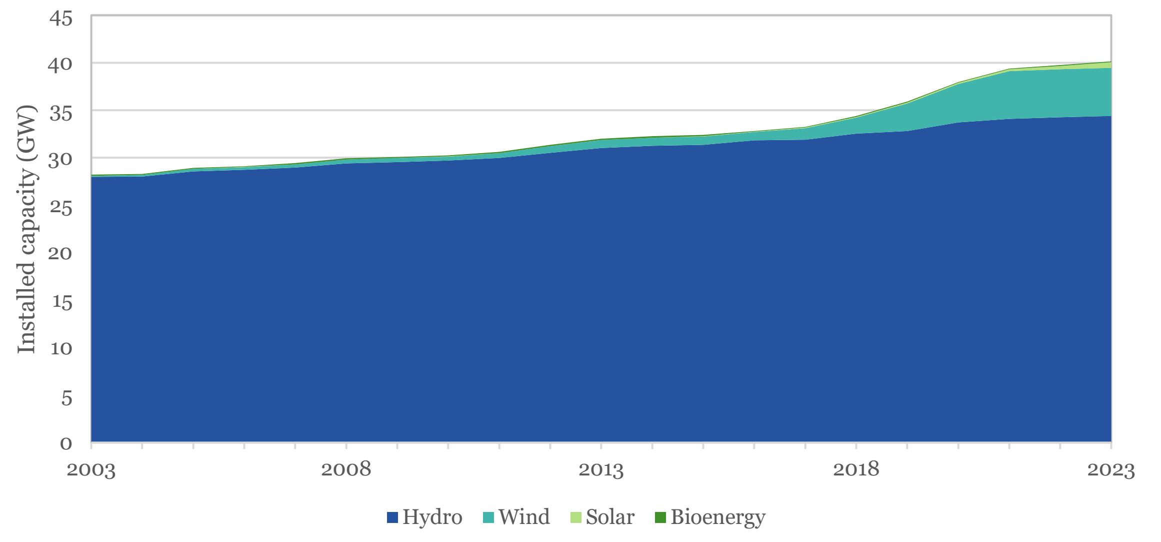

Figure 6. Renewable electricity generation capacity in Norway between 2003-2022 [20].

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. For Norway, these projects include 0.2 GW of onshore wind energy, and 3.3 GW of offshore wind energy, totaling **3.5 GW** of new renewable electricity capacity in the pipeline (Figure 7).

Figure 7. Renewable electricity projects (GW) in pipeline in Norway on data collection conducted in BalticSeaH2.

A competitive advantage for Norway to facilitate hydrogen production with no or low emissions is the production of blue hydrogen via reforming natural gas with CO2 capture, which requires access to power, natural gas, and space for CO2 storage. Due to the vast oil and gas fields, Norway has significant potential to export blue hydrogen to Europe and store associated excess carbon on the Norwegian continental shelf. Creating a pipeline to deliver blue hydrogen to Europe would also have a large development potential.

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 8 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

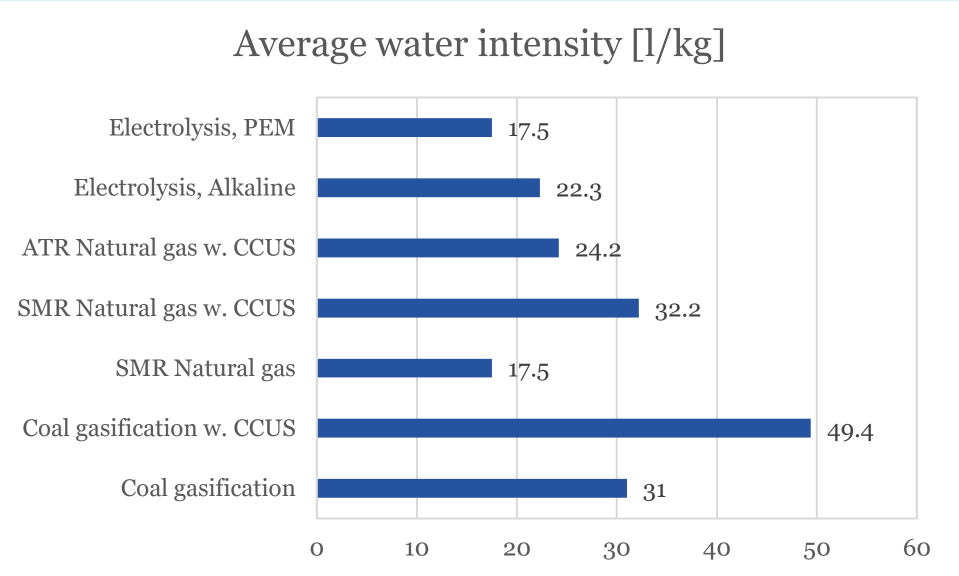

Figure 8. Average water consumption intensities by hydrogen technology [21].

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

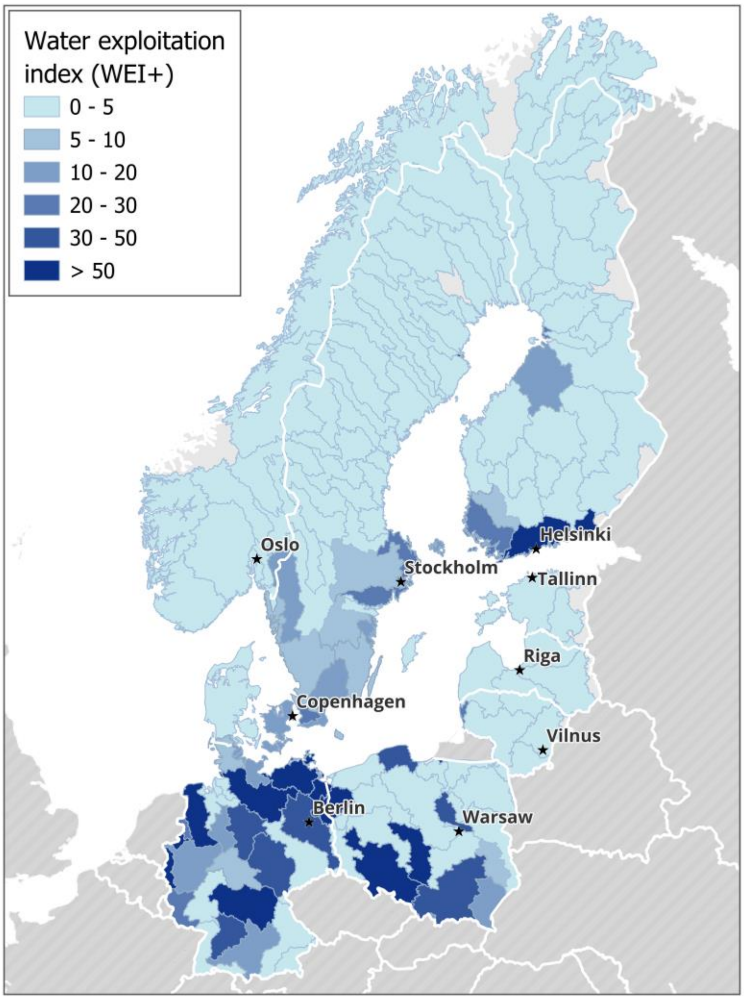

Figure 9. Regional WEI+ values for BSH2 countries in Q3, 2019 [22].

The local water stress conditions determine that 95% of the hydrogen projects that are operating or planned in Norway are in areas with low water stress [21]. The expected hydrogen projects involving water electrolysis would raise hydrogen production in Norway by 630 kt/a, which means an extra 12.5 million m^3 of water use (assuming average use of 19,9 l/kg between PEM and AEL). In general, Norway does not face water scarcity and its yearly WEI+ is 0.07%, which is the lowest among the analysed countries in the Baltic Sea region. However, yearly calculations of the WEI+ at the national level do not account for uneven spatial and seasonal distribution of resources and may therefore hide water stress that occurs on a seasonal or regional basis.

WEI+
0.07%
Baltic Sea region: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (<0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Norway has total of 24.7 Mt/year CO2 available (when calculating industrial sources larger than 0,1 Mt/year), and of that 23.4 Mt/year is from fossil sources, and 1.4 Mt/year from biogenic ones. Yet, information was not retrieved for all CO2 sources: 10.80 Mt/year is uncertain (can be seen on the map below in blue colour). Classified CO2 amounts are fossil CO2 12.47 Mt/year, and biogenic 1.41 Mt/year. However, the uncertain CO2 sources are most likely fossil, as they are located on the islands, on natural gas or oil fields. Thus, the uncertain CO2 is assumed to be fossil and therefore included in that figure. All CO2 sources are located at or near the coastal area of Norway (Figure 10). As most of the CO2 is of fossil origin, the options for power-to-x are more limited. However, there could be some possibilities to take advantage of the fossil CO2 infrastructure, for example near the city of Bergen, where the greatest CO2 source is located. Although the CO2 in Bergen is fossil, there could be synergies in CO2 infrastructure for the utilization of the biogenic CO2 as well. These synergies could benefit a possible CO2 hub.

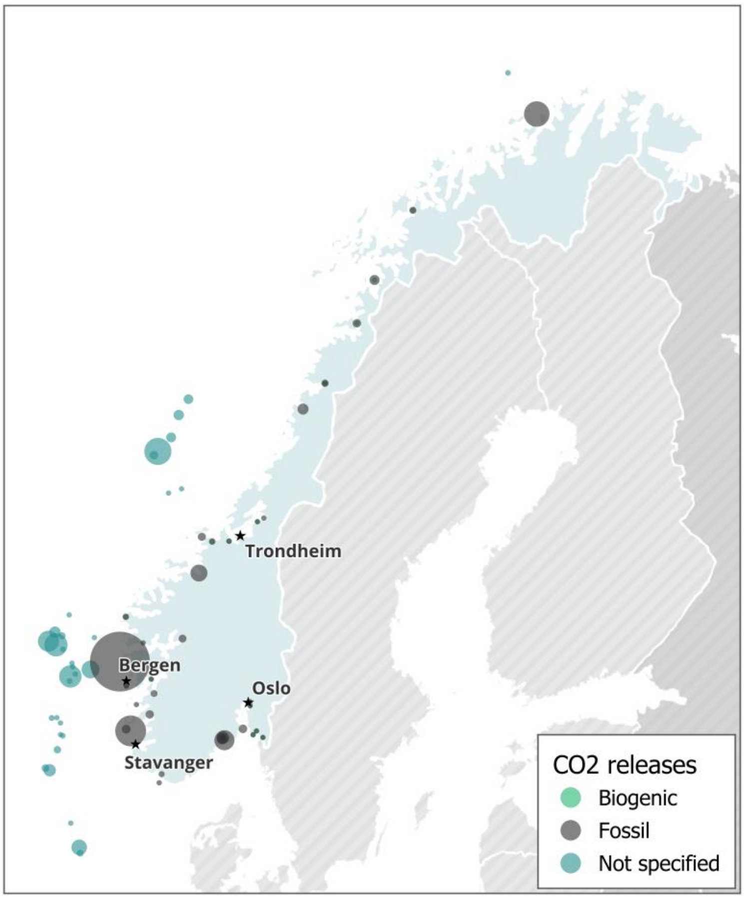

Figure 10. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [23].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

Norwegian Gassco manages a network of gas transmission systems, which includes approximately 9,000 kilometers of subsea pipelines. These pipelines transport natural gas from Norway's continental shelf to European countries, including Germany, Belgium, France, and the UK [24].

The company is currently exploring several options to facilitate the transmission of hydrogen. These include the construction of new dedicated hydrogen pipelines, repurposing existing natural gas pipelines, and the potential blending of hydrogen into the existing natural gas network. By the year 2030, there is a possibility that one of the export pipelines could be repurposed specifically for hydrogen transmission. Additionally, there is consideration for constructing additional hydrogen transmission pipelines, possibly extending to destinations such as the Netherlands, as a long-term solution. Furthermore, it has been highlighted that depleted oil reservoirs could potentially serve as sites for hydrogen or carbon storage in the future. Norway has also a unique opportunity to supply blue hydrogen to Europe by the mid-2030s, switching to green hydrogen later as the infrastructure is ready, estimated in the 2040s. Notably, natural gas has been identified as a key competitive advantage in Norway's hydrogen industry [24].

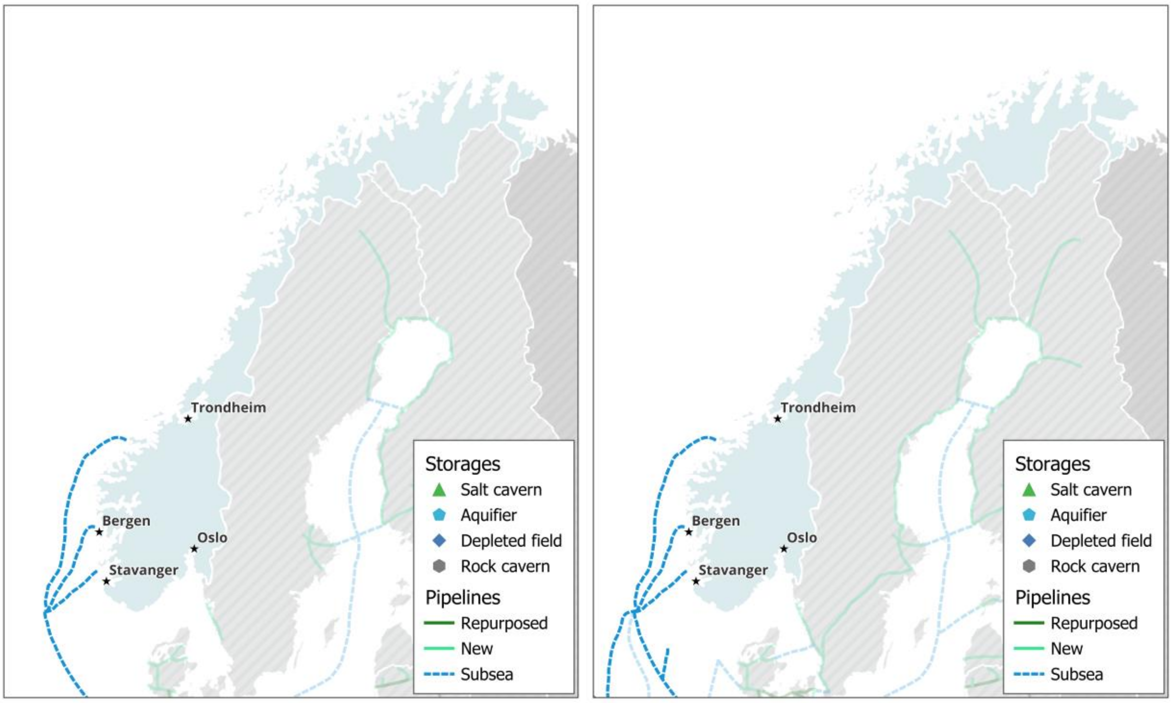

Figure 11. Left: A European hydrogen infrastructure vision for 2030. Right: vision for 2040 [25].

The Norwegian and German authorities signed in 2023 a joint declaration on strengthened cooperation in the hydrogen sector. The declaration confirms, among other things, an intention to secure large-scale supply of hydrogen from Norway to Germany by 2030. This must be based on a step-by-step and industry-driven approach where one explores the technical and economic feasibility of such solutions. As a follow-up to the joint declaration with Germany, an industry-led feasibility study has been initiated to reveal whether a hydrogen value chain between Norway and Germany is technically and practically feasible. The work is led by Gassco from Norway and Dena (Deutsche Energie-Agentur) from Germany. The study investigates and compares different alternatives for hydrogen export from Norway to Germany. This includes several possible locations to produce hydrogen in Norway and transport through a new or repurposed hydrogen transmission pipeline. In addition, an alternative where hydrogen is produced in Germany with gas from Norway and where captured CO2 is transported back to the Norwegian continental shelf is included. CO2 infrastructure from Belgium to Norway is also considered, as well as CO2 transport by ship [19].

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [26]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which only salt cavern has reached industrial maturity in storing pure hydrogen. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

Norway has a large hydropower capacity, which makes the energy system best adapted among the BSH2 countries to balance the variability that increasing weather-dependent renewable electricity causes. However, significant hydrogen use is expected in the Swedish industrial sector, for which large-scale hydrogen storage can help to lower the cost and ensure the reliability of hydrogen supply.

Norway does not have current large-scale hydrogen storage capacity. However, Norway has a theoretical UHS capacity of 640 TWh in shut down oil and gas fields [27]. Storage of pure hydrogen in depleted oil and gas fields requires further research regarding the geochemical reactions between hydrogen, the storage media, and residual hydrocarbons. There are no salt formations in Norway.

Hydrogen production plans

Based on data collection conducted in BalticSeaH2, many hydrogen projects in varying degrees of maturity are currently in development in Norway, with total estimated electrolyzer capacity of up to **3.3 GWe**, once the projects have reached their final phase. It is worth noting that many of the projects in early stages have not disclosed any information regarding their planned production capacities or volumes and are hence excluded from this value.

While not all projects have disclosed their individual capacities, they may have provided estimates of the annual hydrogen production volumes (kt/a). Assuming a 65% electrolyzer efficiency and year-round operational availability for projects that have only provided information of the expected electrolyzer capacity (MW), the planned hydrogen production volume in Norway would be above **620 kt/a** by 2030. The current hydrogen production capacity in Norway is approximately 288 kt/a, indicating that if all currently planned projects were to be realized, Norwegian hydrogen production capacity would increase more than twofold.

In the Figure 12 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project. As can be seen, the projects are primarily situated along the coastal regions of Norway.

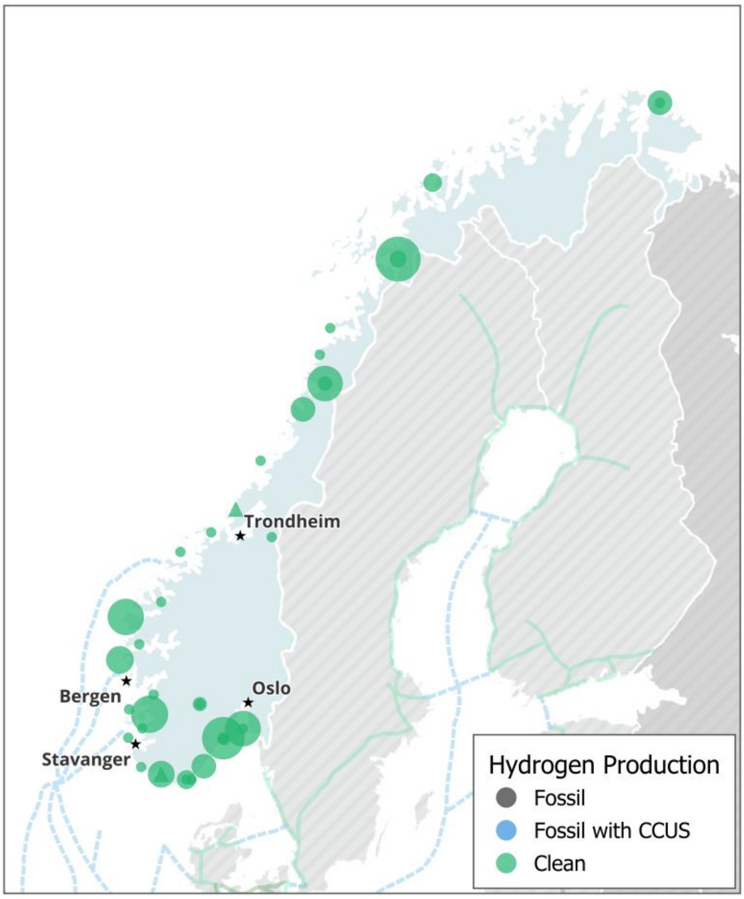

Figure 12. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

Hydrogen production for the fertilizer industry appears to be a prominent trend among planned projects in Norway as based on the collected data, a significant portion of the planned electrolyzer capacity (2.4 GW) will at least partially supply hydrogen for ammonia production. Most of the planned projects also include plans for hydrogen supply to transport and logistics.

Based on public announcements, the following large-scale clean hydrogen production projects have already received final investment decision or are currently being constructed in Norway:

- SKREI is **Yara's** initiative to build and produce clean hydrogen with **24 MW** capacity at Yara's ammonia production facility at Herøya Industripark in Porsgrunn, Norway [9]. The project has received NOK 283 million support from ENOVA. The plant is currently under construction and the initial plan was to start up the operations in 2023.

- Hydrogen Hub Agder, a joint venture between **Everfuel** and **Greenstat**, has reached its final investment decision in early 2024 [28]. Supported by NOK 148 million ($14.9 million) from Enova in 2022, the project will start with a **20 MW** electrolyzer and expand it later to **60 MW**. Construction is scheduled to begin in autumn 2024, with a primary focus on supplying fuel for the shipping industry.

The cumulative capacity of hydrogen production projects in Norway is presented in Figure 13. Note that several large projects in early conceptual stages have not stated the planned commissioning year. In this case, the project is expected to be operational in 2030 or beyond. Additionally, projects without specified capacity or annual production have been excluded from the graph. High production capacity in 2030 and later shows that many of the projects are still in initial phases and have not indicated the planned start-up year yet.

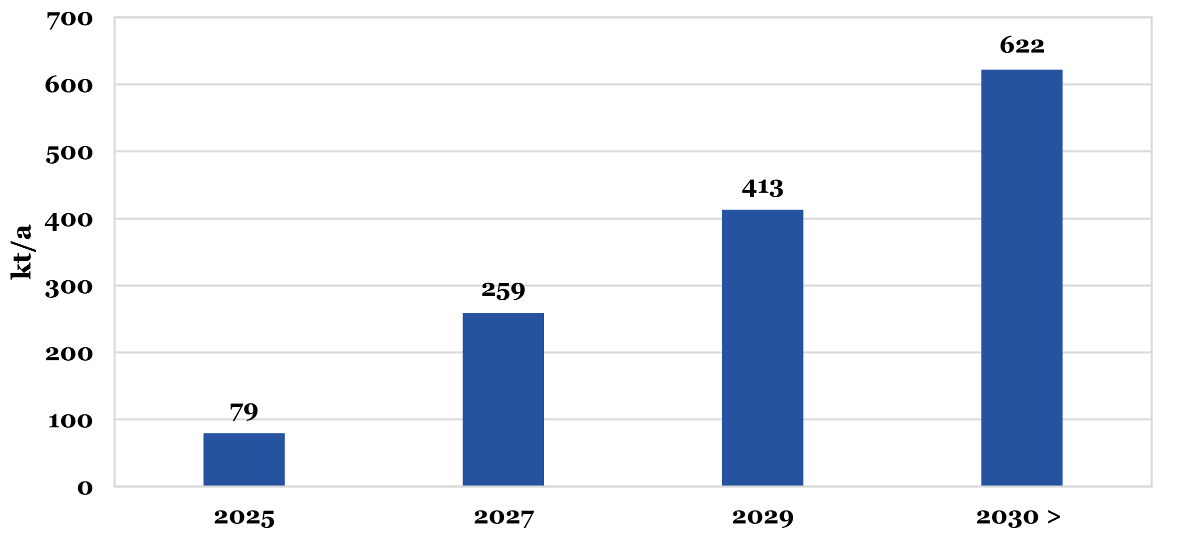

Figure 13. Cumulative capacity of clean hydrogen production projects in Norway based on data collection conducted within BalticSeaH2.

Potential geographical areas for hydrogen development

Vestfold and Telemark: Herøya is one of the largest industry areas in Norway and has established a local hydrogen network. NEL Hydrogen in Notodden, outspring from Hydro, are foreseeing a growth from larger contracts, amongst others with Nikola Motor, USA.

Trøndelag: Aims to play a vital role in the hydrogen value chain and intends to enhance the establishment of a robust regional infrastructure for renewable and fossil-free fuels including hydrogen. Europe's first hydrogen trucks are operated by ASKO Midt-Norge, located in Trondheim. Also, there is an initiative to develop a hydrogen valley in this region.

Troms og Finnmark County: Adopted a hydrogen strategy and intend to utilize the natural advantages to produce hydrogen, both from natural gas and wind power. The EU-project Haeoulus operates a new-generation electrolyser integrated within a state-of-the-art wind farm in a remote area with access to a weak power grid, located at Raggovidda in Finnmark.

Nordland county: The Vestfjorden Ferries operating the route between Bodø and the Lofoten islands will use hydrogen from 2025. The city of Bodø is the regional capital of Nordland County and a centre for logistics and transport. The goal is to realize zero-emission transport systems within the next decades. Hydrogen is expected to play a key role in this ambition with production of 5 to 40 tonnes per day.

Vestland: Equinor plans a production of 0,5 million tonnes per year within 2030 (about 1 400 tonnes per day).

Møre og Romsdal: Aukra Hydrogen Hub plans for a production of 1 200 tonnes per day of clean hydrogen using natural gas from the local gas processing plant at Nyhamna.

Rogaland: Dalane Energi and Hydrogen Solution (HYDS) opened a new clean hydrogen production facility with 1 MW electrolyzer capacity in Egersund harbor to produce clean hydrogen (140 t/a) for commercial purposes, such as for a neighbouring fish feed factory. The construction was completed in 2023 at a cost of 45 million NOK. The project received support from various sources, including the EU's ROBINSON project, which aimed to reduce fossil fuel dependence in island communities. The facility has the potential for future expansion, increasing its capacity from 1 MW to 6 MW. After the expansion, surplus heat and oxygen generated could be utilized in a nearby shrimp farm.

Education and employment

The hydrogen industry needs people with general degree education within, among others, engineering, mathematical and natural science subjects, as well as economics, ICT, and law. Within the engineering and technical areas, automation, process engineering, electrical and electric power, machine and mechatronics, nanotechnology, and materials science, as well as chemistry are focus areas.

There are many educational programs related to energy and environmental technologies in Norway. Norwegian University of Science and Technology (NTNU) offers a program in Hydrogen Systems and Enabling Technologies, focusing directly on hydrogen. In Western Norway University of Applied Sciences, there is a program called Sustainable hydrogen technology. Many programs offer courses related to hydrogen, and there is a wide offering on programs for upskilling and reskilling in the form of hydrogen technology courses. An overview of educational programmes that are relevant in hydrogen development in Norway:

- NTNU: Hydrogen Systems and Enabling Technologies, Chemistry, Nano technology, Materials Science and Engineering, Energy and environment, Master of Science in Sustainable Chemistry and Biochemical Engineering, Material technology, Industrial chemistry and biotechnology, Innovative Sustainable Energy Engineering, Electric Power Engineering Master, Environmental Engineering, Product development and production, Sustainable energy.
- University of Tromsø: Electrical engineering
- University of Stavanger: Environmental technology, Energy, reservoirs, and geoscience
- University of Agder: Renewable energy, Mechatronics
- Norwegian University of Life Sciences (NMBU): Renewable energy, Chemistry
- University of southwest-Norway: Energy and Environmental Technology, Electrical Power Engineering
- University of Bergen: Energy (civil engineer), Energy- and process technology, Chemistry, Nanoscience
- College of Østfold: Green Energy Technology
- University of Oslo: Chemistry, Renewable energy systems, Materials science for energy and nanotechnology
- Western Norway University of Applied sciences: Sustainable hydrogen technology

Hydrogen related research is carried out in NTNU, SINTEF, NORCE, HVL, USN, University of Oslo, University of Bergen, and Western Norway University of Applied Science. SINTEF runs a Norwegian research initiative called Hydrogeni, and NORCE another called HyValue.

Norway has cooperation in hydrogen with Germany related to goals to large-scale hydrogen supply from Norway to Germany. They have a joint declaration and feasibility study initiated. CO2 infrastructure from Belgium is also considered, as well as CO2 transport by ship.

In higher education at the university and college level, several players in Norway's oil and gas industry are already addressing the challenge of hiring enough people with the right skills, particularly in engineering and technological fields. Consequently, this shortage of skilled workforce is expected to impact the hydrogen value chain, as companies will struggle to find the necessary talent.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [29]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [30]. Recent survey [31] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [32]. The rise of right-wing politics and growing “greenlash” against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [33].

Another barrier potential barrier stems from a community-rejection (sometimes referred to as the NIMBY-effect, “Not In My Backyard”), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [34], [35], [36], [37], [38]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [39].

The success of this community ownership model in driving Denmark’s wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [31], [32] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

There remains little research on the socio-political and community acceptance of hydrogen technologies in Norway [30]. However, looking at Norwegian public opinion on different sources of energy, there seems to be rather high public support for renewable energy, such as wind, solar, and particularly high support for hydropower [29]. On the other hand, in the recent years, Norway has faced turmoil concerning local opposition to wind power. As a response of a 2019 national framework for wind power, local opposition rose across the country, with 49 out of 56 municipalities rejecting wind power in their region, leading the government to stop all new approvals for wind projects [40]. According to different accounts, the opposition stemmed from a variety of concerns, ranging from landscape and tourism issues, place attachment, environmental concerns, and lack of sufficient compensations and consultations with local communities and municipalities [41]. One publication also tackles the relationship between social acceptance, hydrogen, and wind power, stating that hydrogen on its own will not save onshore wind power from opposition, but if it contains a local purpose, more citizen support can be gained [42]. This suggests that hydrogen initiatives should be closely coordinated with municipalities and other local actors, to mitigate potential conflict and ensure valuable contribution from hydrogen initiatives to local economies and environments.

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Appendix E

Country profile Denmark

Contents

Summary of national opportunities and challenges

Opportunities	Challenges
Significant offshore wind power growth potential	Large hydrogen infrastructure development needs
Large export potential to Germany – strong collaboration with Germany on infrastructure projects	Wind power project delays have created uncertainties to sufficient clean power supply
Socially sustainable approach to energy infrastructure projects	Tedious and time-consuming permitting processes
High level of support for green initiatives at political and social level	Political interest in CCS over CCU – uncertainties in availability of low-cost CO_2 for hydrogen derivative production
Pre-existing mechanisms and legislation for facilitating benefit-sharing over green initiatives	No clear vision about clean hydrogen usage apart from export to Germany
Demand for hydrogen derivative products especially in the maritime sector	Low public awareness of hydrogen technologies

National hydrogen strategies and targets

The Government's strategy for Power-to-X [1] was published in 2021 by Danish Ministry of Climate, Energy and Utilities, and approved in 2022 [2]. The strategy sees several strengths that will promote Denmark in the production and use of hydrogen and Power-to-X (PtX). These include but are not limited to: considerable offshore wind resources, available biogenic CO2 from biogas plant and biomass-fueled combined heat and power (CHP), strongly positioned Danish companies throughout the value chain, strategic geographical location in terms of exporting PtX products and technologies. The strategy has established four main objectives to promote PtX in Denmark and within the report, describes Government actions to achieve these objectives. The objectives are as follow:

1) **Power-to-X must be able to contribute to the realization of the objectives in the Danish Climate Act.**
   PtX technologies should be promoted in sectors where direct electrification is not possible or economically feasible, such as part of the industrial and heavy-duty transport sectors, shipping and aviation.
2) **The regulatory framework and infrastructure must be in place to allow Denmark's strengths to be utilized and for the Power-to-X industry to operate on market terms in the long run.**
   The right regulatory framework is needed to be established for PtX to compete with other fossil fuels. In addition, Government support schemes will take place. The Government will, for instance, introduce **an auction of DKK 1,25 bill for establishment of PtX facilities** to support industrialization and upscaling of PtX production in Denmark and thereby reduce the costs of green hydrogen production.
3) **The integration between Power-to-X and the Danish energy system must be improved.**
   Flexible electrolysers are a measure to balance variable renewable electricity production.
4) **Denmark must be able to export Power-to-X products and technologies.**

Hydrogen Strategy/Roadmap
Yes
The Government's strategy for Power-to-X (2022)

The Government target for electrolyzer capacity is 4-6 GW by 2030 and that the capacity expansion would occur in market terms to the greatest extent possible.

Quantified targets for hydrogen production
Yes
•4-6 GW electrolyzer capacity (2030)

National networks

Hydrogen Denmark: Main business organisation bringing together stakeholders within the areas of hydrogen, PtX and fuel cells [3].

Danish Hydrogen Alliance: A strategic partnership between Hydrogen Denmark, Danish District Heating Association, Dansk Metal and DI Energy. The partnership aims at strengthening industrial development and upscaling of green hydrogen and PtX in Denmark [4].

Green Power Denmark: Non-commercial business organisation for the green energy value chain in Denmark. The organisation was formed in 2022 as a merger between Danish Energy, Wind Denmark and Solar Power Denmark [5].

Energy Cluster Denmark: National cluster organisation representing the entire Danish energy sector with +500 members. The cluster is a neutral, value-creating and member-driven innovation platform for establishing and facilitating innovation collaborations between small and large companies, knowledge institutions and public players throughout the energy sector [6].

Hydrogen state-of-play

In Denmark, hydrogen production primarily relies on the reforming of fossil-based fuels (Figure 1). Hydrogen is mainly used in the refining industry. Compared to neighbouring countries around the Baltic Sea, Denmark's production capacity (31 kt/a) and consumption (25 kt/a) of hydrogen is rather limited.

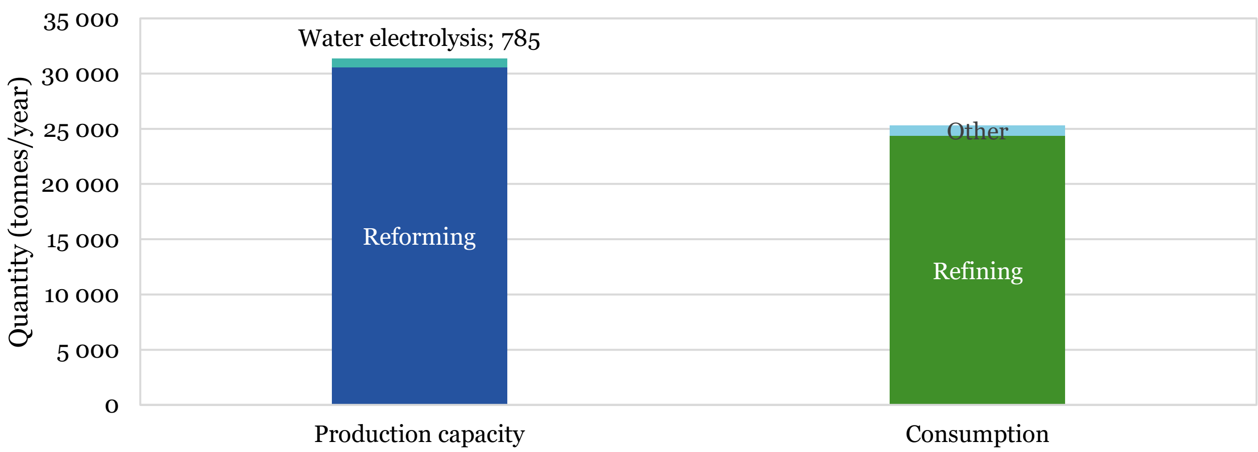

Figure 1. Hydrogen production and consumption in Denmark [7].

The annual dedicated hydrogen production in Denmark is approximately **31 kt/a**, of which 0.8 kt/a is based on water electrolysis. Assuming that 30 kt/a of hydrogen is produced by steam methane reforming (SMR) with emissions of 9 kgCO2/kgH2, decarbonising Denmark's fossil-based hydrogen production would lead to 275 kt of CO2 reduction, which corresponds **0.6 %** of Denmark's total CO2 emissions (total emissions 2021: 45 515 kt CO2-eq excl. LULUCF [8]). The location of the operational hydrogen production facilities is presented in Figure 2.

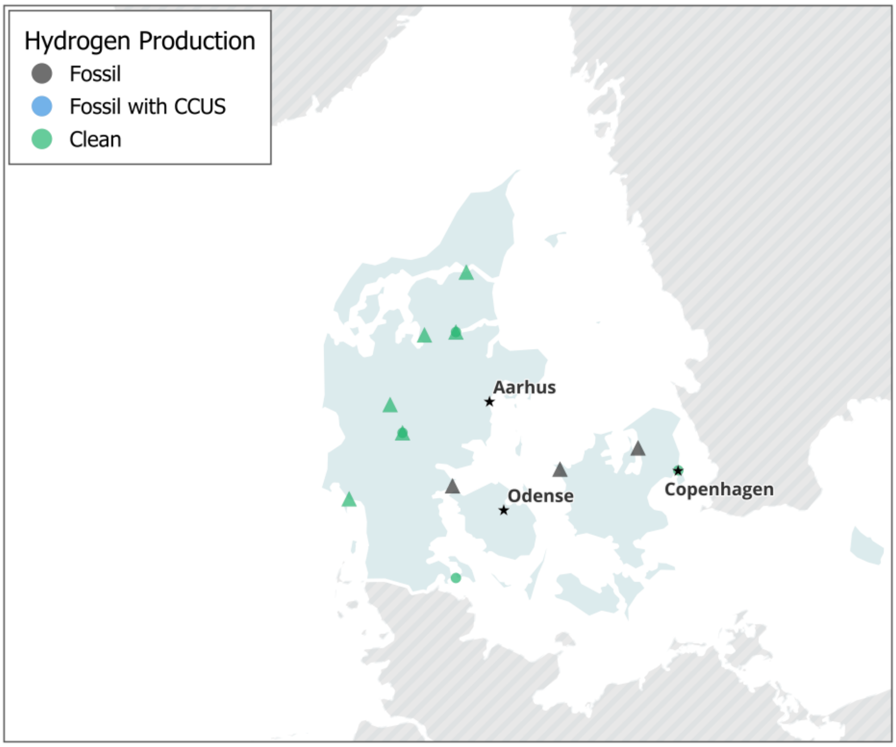

Figure 2. Operational hydrogen production facilities. Facilities with unspecified capacity indicated by triangle markers [9].

Existing hydrogen consumption sources	CO_2 reduction potential in fossil hydrogen production
25 kt/a	**0.6%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [10]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel [11].

Denmark has two refineries with capacities of 3.5 Mt and 5.6 Mt of crude oil annually [12] in which fossil hydrogen could be replaced with a clean alternative. In fact, in the smaller refinery of Crossbridge energy, a clean hydrogen production project HySynergy is under construction to supply clean hydrogen for the refinery, with target electrolyzer capacity of 1 GW by 2030 [13]. Locations of these example industrial plants with potential for clean hydrogen use in decarbonisation are mapped in Figure 3.

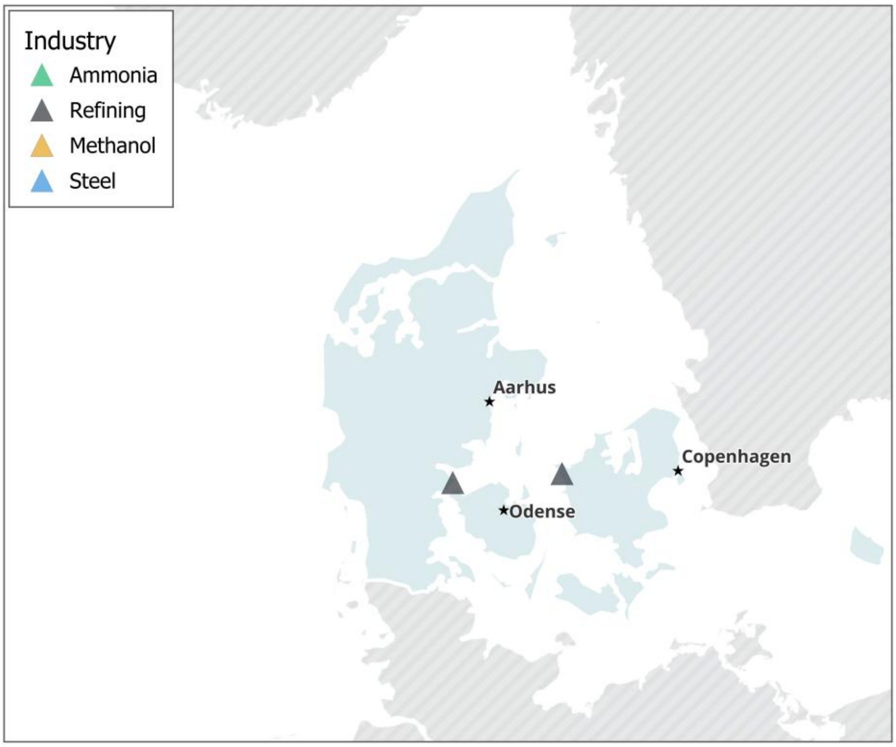

Figure 3. Locations of example industrial plants in Denmark with potential for clean hydrogen use in decarbonisation.

Ammonia production	Refineries	Steel production
No	**9.1 Mt/a (crude oil)**	**No**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxis, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in

agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

The main domestic market for hydrogen is in the transportation sector. In the shipping industry, there are various projects that aim to convert engines to methanol and ammonia. Methanol has been widely talked about for the maritime sector. This was shown when Mærsk ordered 19 vessels that run on methanol, and the first one started operating in 2023. There are also projects that focus on SAF, which Danish politicians have mentioned several times as important for the green transition in Denmark.

It is likely that liquid or gaseous fuels will eventually dominate the energy consumption in the long term because of the limited potential of direct electrification, which is not expected to happen soon either. This is also supported by the State of Green mapping, where the three consumption hubs are at or near industry harbours (Aarhus Habour, Greenguard Esbjerg Harbour, and Bornholm Bunker Hub). For example, an electrolyzer unit is being built at Port of Esbjerg to produce hydrogen for ships powered by fuel cells [14].

For road transport, it is unclear how much PtX should be used for some applications. This is mainly because of the possibility of introducing direct electrification in the sector. Where it is not possible, the Danish Energy Agency has evaluated that it will be possible to raise the share of PtX fuels, other than hydrogen, in the remaining cars that use internal combustion engines until they are replaced by EVs [15]. These include fuels such as methanol, e-gasoline, and e-diesel, which will require retrofitting of some engines/vehicles. It should be noted that this potential solution is not the most-efficient or climate-friendly in the long term. PtX also has the potential to be used in the industrial sector's internal heavy road transport, but the Danish Energy Agency estimates that not all segments can be covered by 2030. Instead, it can be expected that this potential will be realized closer to 2050, where it is then estimated that the potential will increase significantly.

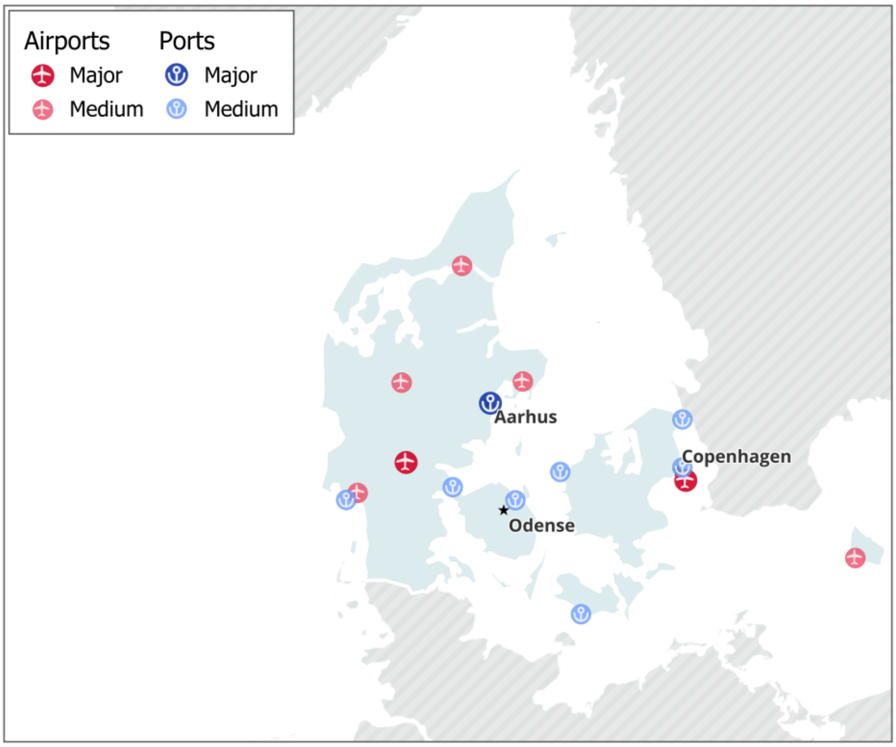

Figure 4. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) *[16].*

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
93%	**58% (58 ktoe)**	**121 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [17]

Hydrogen refueling infrastructure

Everfuel operated five hydrogen refueling stations (HRS) for passenger vehicles in Denmark, however, the company announced in September 2023 that it will either "close or pause, and if possible, divest or repurpose" operations of the refuelling stations [18]. Three of the stations, located in Brabrand, Kolding and Copenhagen, were completely shut down and two stations located in Copenhagen and Port of Aarhus (as located on the map), were paused in operations until further notice. The reason for closing or pausing the refuelling stations were lack of hydrogen demand, unprofitability of operations and considerations regarding the technical lifetime of the refuelling stations.

Vireon AS, a subsidiary Norwegian Hydrogen, is planning to build HRSs to Denmark. The company plans to build a refueling station corridor from Northern Finland via Sweden and Denmark to the continental Europe. The company has recently (4/2024) received a 9.2 m€ grant from EU to aid building seven refueling stations to Denmark and Finland, serving both heavy-duty and passenger vehicles [19]. In Denmark, the three refueling stations will be located in northern Jutland, Vejle, and Padborg. The four additional refueling stations funded will be constructed in Finland. In Northern Jutland, Norwegian Hydrogen is also coordinating an EU-funded Hydrogen Valley project CONVEY [20], in which an integrated hydrogen ecosystem in planned to be established at the at the Port of Hirtshals. The refueling station will be a part of this ecosystem, which also includes a 5 MW electrolyzer, and distribution networks for hydrogen, oxygen, and heat.

Figure 5. Operating and planned hydrogen refueling stations based on *[21], [22]* and publicly announced projects.

Resource availability

Renewable electricity production

Denmark has for many years been a leading nation when it comes to wind power, both in academia and industry. Given its position between the North Sea and the Baltic Sea, there is substantial opportunity to significantly increase wind power production. With the Esbjerg declaration [23], Denmark and its North Sea neighbors committed themselves and each other to the ambitious aim of reaching a capacity of 65 GW offshore wind by 2030 and 150 GW by 2050. The Danish goal for offshore wind capacity in the North Sea was in this connection set at 10 GW by 2030 and 35 GW by 2050.

To accelerate the installation of new onshore capacity, the Danish Government has in 2023 conducted a screening of areas most suitable for GW scale energy parks. The screening was done in collaboration with municipalities and companies and resulted in a list of 32 identified areas suitable for large energy parks [24]. The screening will be followed up by a dialogue with municipalities and VE operators. The energy parks will be ideal to combine with onsite or nearby production of hydrogen or hydrogen derivatives.

In 2020 and 2021, Danish TSO Energinet and Green Power Denmark published a capacity map of the Danish electricity grid to pave the way for new onshore renewable energy facilities [25]. The map shows available grid capacity and demand locally and serves as a guidance for where new facilities could most easily be connected to the grid and is a useful tool when determining the location of PtX facilities.

The recent trends in renewable electricity generation capacity in Denmark are illustrated in Figure 6. Both wind and solar capacities have increased over the last decades, and solar power capacity has increased quite rapidly in the past few years.

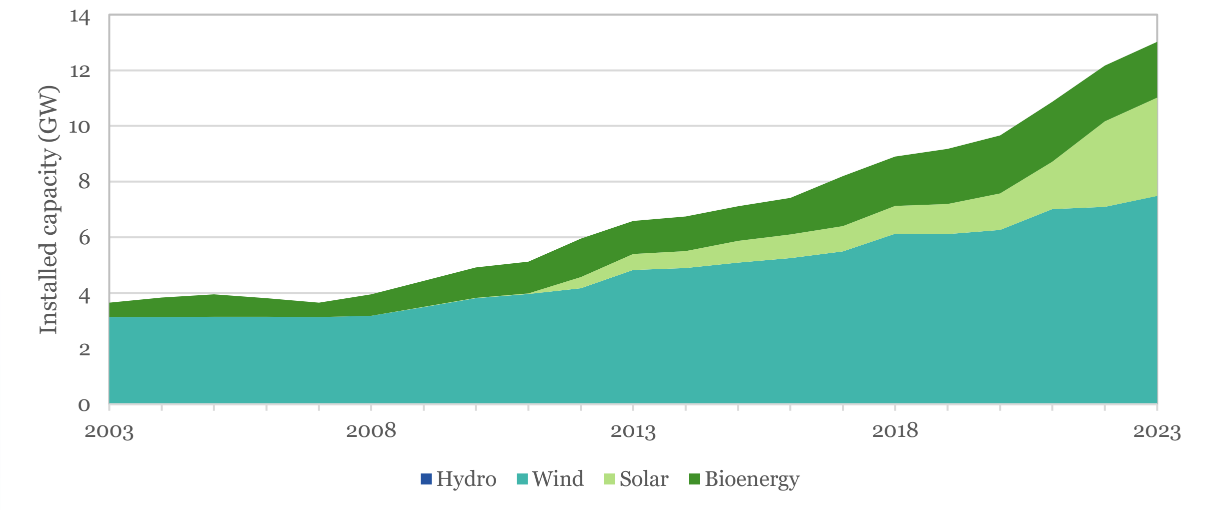

Figure 6. Renewable electricity generation capacity in Denmark between 2003-2022 [26].

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. As of October 2023, these projects for Denmark include 3.9 GW of solar energy, 0.1 GW of onshore wind energy, and 14.9 GW of offshore wind energy, totaling **18.8 GW** of new renewable electricity capacity in the pipeline (Figure 7). In fact, the most important driver behind the growth of the clean hydrogen industry in Denmark is the high renewable electricity potential for clean hydrogen production. Although several offshore projects have recently been cancelled, there are excellent conditions and ambitious targets for the development of offshore wind. For instance, a new offshore tender of 6 GW was announced in April 2024 (not included in the analysis).

Figure 7. Renewable electricity projects (GW) in pipeline in Denmark on data collection conducted in BalticSeaH2.

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 8 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

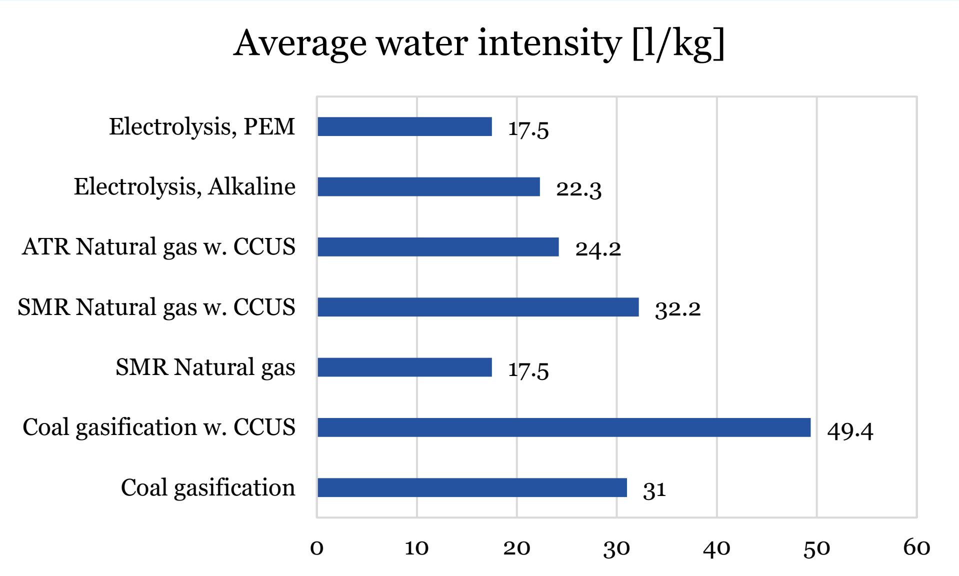

Figure 8. Average water consumption intensities by hydrogen technology [27]

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% generally signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

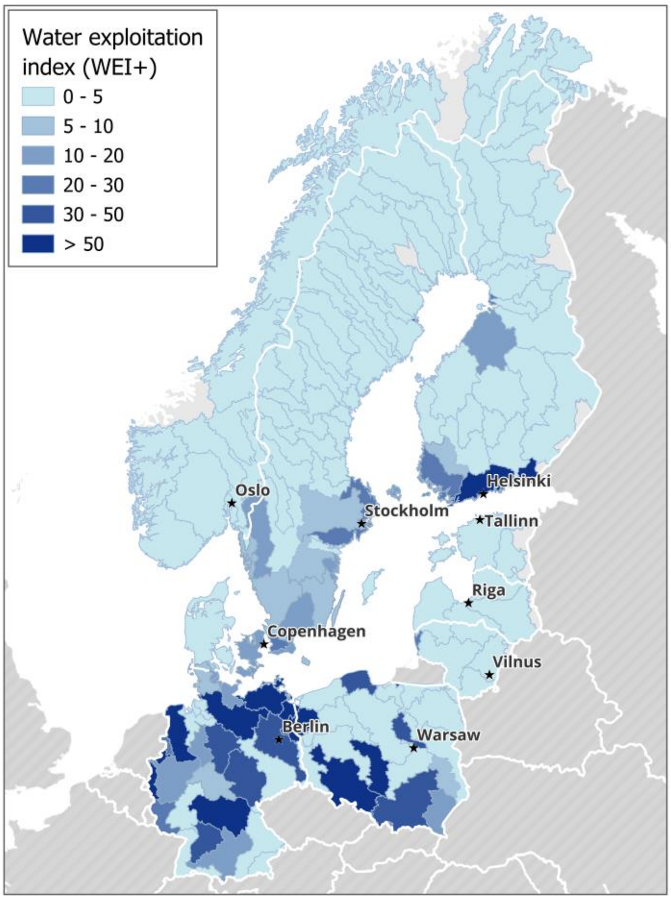

Figure 9. Regional WEI+ values for BSH2 countries in Q3, 2019 [28].

The local water stress conditions determine that 2% of the hydrogen projects that are operating or planned in Denmark are in areas with low water stress, 13% in areas with low to medium water stress, 83% in areas with medium to high water stress, and 2% are in areas with high water stress. The expected hydrogen projects involving water electrolysis would raise hydrogen production in Denmark by 2 260 kt/a, which means an extra 45 million m^3 of water use (assuming average use of 19,9 l/kg between PEM and AEL). In general, Denmark does not face water scarcity and its yearly WEI+ is 2.72% (2019) [28]. However, yearly calculations of the WEI+ at the national level do not account for uneven spatial and seasonal distribution of resources and may therefore hide water stress that occurs on a seasonal or regional basis. For instance, Zealand experiences higher water stress compared to the rest of Denmark.

WEI+
2.72%
BSR range: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (< 0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Denmark has a total of 11.5 Mt/year of CO2 available (when calculating industrial sources larger than 0,1 Mt/year). The greatest concentration of CO2 can be found in the Northern Denmark, around the city of Aalborg (Figure 10). Other relatively significant locations are near cities of Esbjerg and Aarhus, and smaller ones in, e.g., Copenhagen and Odense. In case the CO2 emissions are biogenic, there could thus be possibilities for PtX production.

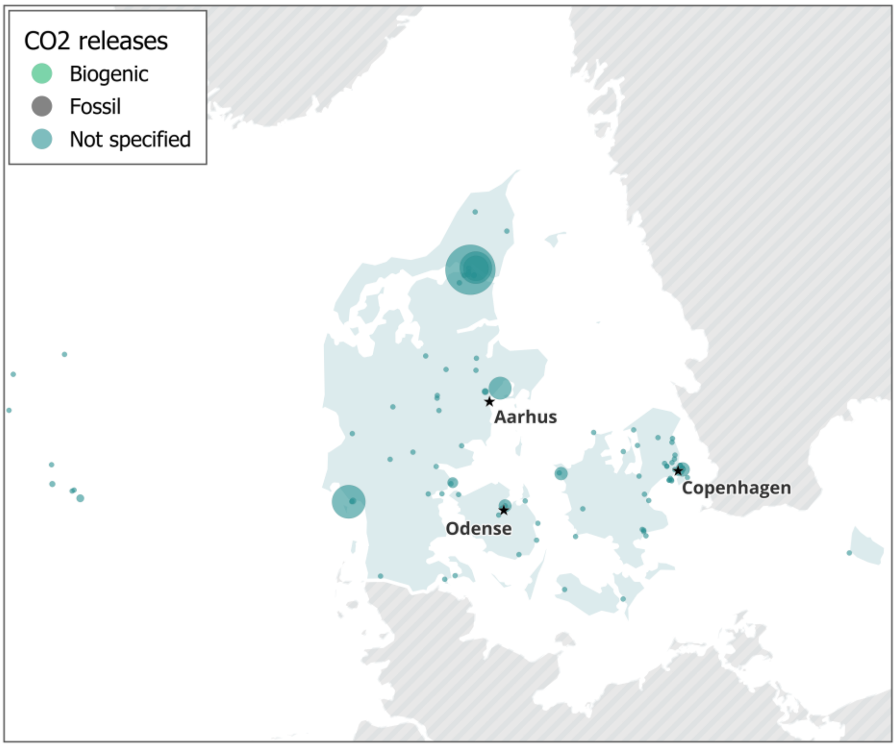

Figure 10. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [29].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

Denmark currently has a natural gas transmission pipeline spanning around 1 250 kilometers [30]. The pipeline is interconnected with Germany and Sweden. In 2022, a new pipeline called the Baltic Pipe was commissioned to serve the purpose of transporting natural gas from Norway, passing through Denmark, and onwards to Poland and nearby countries [31].

For hydrogen transmission via pipelines, Denmark's electricity and gas TSO Energinet is assessing whether a 93 km section of the natural gas pipeline would be suitable to be repurposed to transmit hydrogen [31]. A political agreement was made in April 2024, which sets the frame for the financial conditions of a new hydrogen infrastructure in Denmark. The key message of this agreement was that the build-out of a hydrogen infrastructure will be based on actual financial commitment from the industry [32]. Additionally, a collaboration agreement between Denmark (Energinet) and Germany (Gasunie Germany) was made in March 2023 to connect hydrogen produced in Denmark to the German hydrogen transmission grid [33]. The hydrogen transmission pipeline will connect Western Denmark, under the project name **Danish Backbone West**, and Northern Germany, under the name **Hyperlink 3**, and will run from Lille Thorup, Denmark, to Heidenau, Germany, with a total length of 550 km. The project will be realized between 2028-2030. The planned connection to the German hydrogen grid, allowing for easy hydrogen export through pipelines to the rest of Europe, is a major competitive advantage and an important driver for the development of hydrogen economy in Denmark, and in fact, exports are expected to be a major end-use sector for hydrogen and its derivates in Demark.

When moving towards 2040, several potential development routes for hydrogen transportation are depicted for Denmark, which will coexist with a biomethane grid [31]. In eastern Denmark, hydrogen transmission pipeline connection can be established to link the Copenhagen area to both Sweden and Germany. Additionally, repurposing the Baltic Pipe for future hydrogen transmission, along with the proposal of new subsea connection from Jutland to Sweden are also alternatives. Additional potential route also involves connecting Denmark to the Netherlands via a subsea hydrogen pipeline.

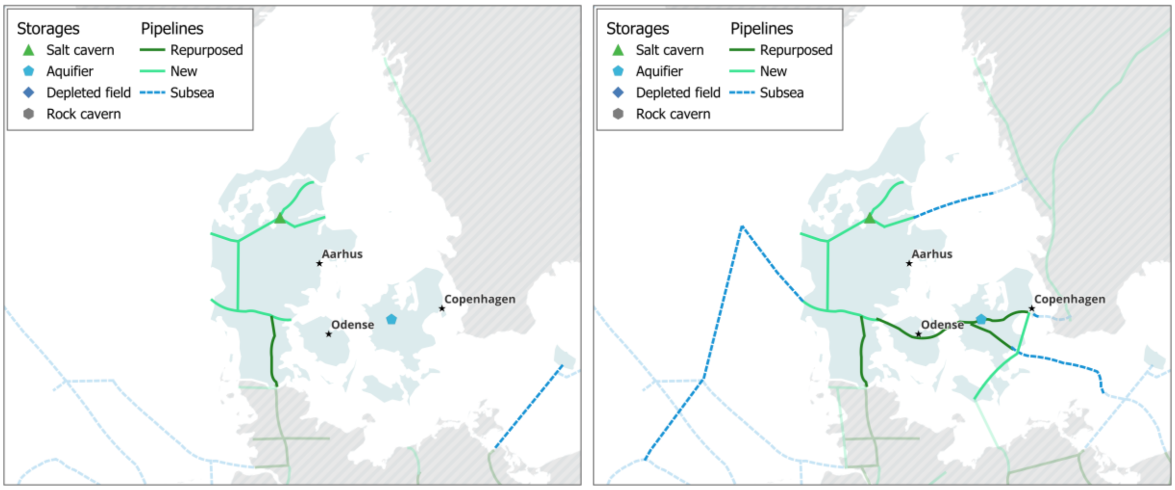

Figure 11. Left: A European hydrogen infrastructure vision for 2030. Right: Vison for 2040 [34].

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity.

However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [35]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which hydrogen is stored predominantly in salt caverns. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

Denmark can significantly benefit from large-scale UHS capacity due to its gigawatt-scale hydrogen project portfolio. Another considerable hydrogen storage aspect is the strong development of wind power in Denmark, particularly offshore. As the wind farms will be located on a rather small area geographically, it can be expected that the volatility of the production will be particularly strong in comparison to, e.g., Sweden and Finland, where wind farms are distributed on a larger area. Hydrogen storage helps to decouple the highly volatile electricity production from consumption, which is essential if the consumption is not flexible. Additionally, Denmark has well-suited geography for UHS with existing gas storage facilities; Gas Storage Denmark A/S owns and operates two natural gas storage facilities, one salt cavern facility, consisting of 7 cavities, in Lille Torup and one aquifer in Stenlille [36]. Hydrogen storage in salt caverns is being developed in Green Hydrogen Hub project [37], with the target of repurposing one cavern in Lille Torup by 2026, and reaching 77 GWh storage capacity by 2030.

Hydrogen production plans

In Denmark, there is a great potential for producing green hydrogen. However, the demand part is yet to be developed, and most of the produced hydrogen is thus likely to be exported, mostly to Germany. The build out of hydrogen production and PtX facilities is already taking place throughout Denmark, also driven by export opportunities to Germany. The total estimated capacity for the projects in the pipeline is approximately **9 GW**. However, some projects have not disclosed any information regarding their planned production capacities or volumes.

While not all projects have disclosed their individual capacities, they may have provided estimates of the annual hydrogen production volumes (kt/a). Assuming a 65% electrolyzer efficiency and year-round operational availability for projects that have only provided information of the expected electrolyzer capacity (MW), the combined planned hydrogen production volume in Denmark surpasses **2 200 kt/a** by 2030.

In the Figure 12 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project. As can be seen, the projects are situated throughout Denmark.

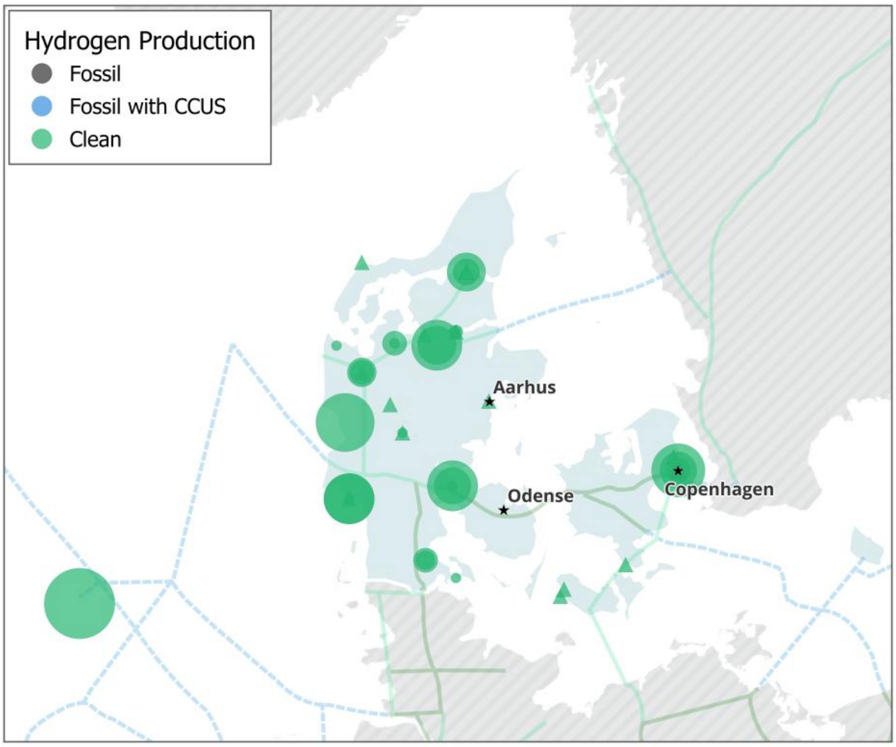

Figure 12. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

Based on public announcements, several large-scale clean hydrogen production projects have received final investment decision or are currently being constructed in Denmark. Examples of those projects are:

- **European Energy and Stiesdal Hydrogen** are collaborating to install a 3 MW electrolysis unit at European Energy's Maade hydrogen plant in Esbjerg. Eventually, the total capacity of the plant will be **12 MW**, which will produce around 270 tons of hydrogen annually when operational. The project, which began construction at the end of 2022, aims to provide clean hydrogen for fuel cell fueled ships in the port and contribute surplus heat to Esbjerg's district heating network. [14]

- **European Energy** is currently also constructing an e-methanol plant in Kassø, near Aabenraa. The e-methanol produced at this facility will serve e.g. as an alternative fuel for shipping. The plant will be equipped with a **60 MW** electrolyzer. [38]

- **Everfuel** is leading a HySynergy project, aimed at establishing a PtX facility for large-scale production and storage of clean hydrogen. The project is divided into three phases, with Phase I currently under construction with electrolyzer capacity at **20 MW**. Phase III targets a capacity of **1 GW** by 2030. HySynergy will play a crucial role in reducing the carbon footprint of Crossbridge Energy's adjacent refinery. The project has received €6.5 million in support from the Danish Energy Agency. [13], [39]

- Skovgaard Energy, in collaboration with the Reddap consortium consisting of Vestas, Topsøe, and EUDP, is presently constructing a P2X demonstration plant for ammonia production in Ramme, West Jutland. The project, supported by a total of DKK 81 million, will have a 10 MW electrolyzer capacity.[40], [41]

As of already operational units, biological PtX plant in Glansager biogas plant by Nature Energy and Andel, produces hydrogen via a **3 MW** electrolyzer from wind and solar. The process involves combining clean hydrogen with CO2 extracted from biogas to produce methane [42].

The cumulative capacity of clean hydrogen production projects in Denmark is presented in Figure 13. Note that several large projects in early conceptual stages have not stated the planned commissioning year. In this case, the project is expected to be operational in 2030 or beyond. Additionally, projects without specified capacity or annual production have been excluded from the graph. High production capacity in 2030 and later shows that many of the projects are still in initial phases and have not indicated the planned start-up year yet.

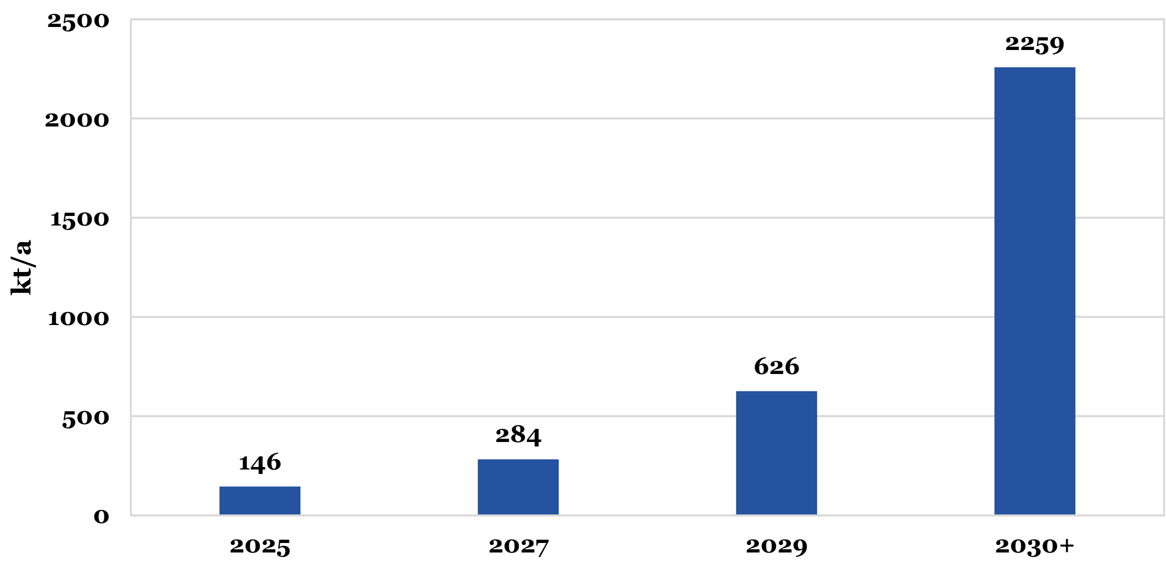

Figure 13. Cumulative capacity of clean hydrogen production projects in Denmark based on data collection conducted within BalticSeaH2.

Potential geographical areas for hydrogen development

The western part of Denmark holds much potential, due to the planned offshore activities in the North Sea along the West Coast. Additionally, it will be easily connected to a planned hydrogen pipeline connected to the German grid.

The southern part of Denmark is seeing much activity within hydrogen technologies and new facilities. The location also eases cross-border collaboration with Germany as well as connection to both offshore wind farms outside Esbjerg and the expected Danish-German pipeline.

The eastern part of Denmark (especially Bornholm and Southern parts of Zealand), which can be connected to the offshore wind farms in the Baltic Sea. Bornholm is well located as connecting point for hydrogen infrastructure in the Baltic Sea region.

The northern part of Denmark is currently working on a European flagship project, Green Hydrogen Hub Denmark, which will deploy electrolysis hydrogen production and long-duration underground storage. Northern Jutland has large caverns which are suitable for creating hydrogen storage in salt deposits.

In addition, the Danish Climate Agreement regarding green electricity and heat “Klimaaftale om grøn strøm og varme 2022” stated that energy parks must include PtX-plants. Thus, the Government proposes to designate 32 energy park areas distributed across 19 municipalities, where the rules and legislations for planning and approving renewable energy facilities will be eased.

Figure 14. Suggested distribution of energy parks in Denmark [42].

Education and employment

Danish universities have many programmes related to energy engineering and technology, and some of them have specialization options to hydrogen, power-to-x, or fuel cells related themes. For upskilling and reskilling of existing workforce, there are two courses. One is about PtX systems, and another one is about PtX technologies, value chains, and sector coupling. Hydrogen-related research can be found in Aarhus University, where there is a Center for Energy Technologies (HIRC), and a project related to Heat and Bubble Transport over Complex Solid Surfaces. There is also a project called Green H2 and MeOH in Denmark (GREMEOH) at the University of Southern Denmark.

There are numerous Danish research initiatives, and they cover the entire hydrogen value chain. Denmark has cross-border joint research initiatives with South Korea and Australia, and they are part of a European project called GreenHyScale and a joint venture called H2 Energy Europe.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [43]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [44]. Recent survey [45] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [46]. The rise of right-wing politics and growing "greenlash" against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [47].

Another barrier potential barrier stems from a community-rejection (sometimes referred to as the NIMBY-effect, "Not In My Backyard"), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [48], [49], [50], [51], [52]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [53].

The success of this community ownership model in driving Denmark's wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [45], [46] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

In the Danish context, literature on the socio-political and community acceptance of hydrogen technologies is still scare, and a recent report indicates that awareness of hydrogen technologies is among the lowest in Denmark (63%) in EU comparison [45]. Thus, further awareness-raising and exploration of public and community sentiments over hydrogen is needed to facilitate the successful deployment of the hydrogen economy.

Unlike in other countries in the Baltic Sea region, wind power is less likely to become a key barrier, due to the country's long history of community-centered approaches and existing legislation of community ownership models. Applying similar pre-existing community-approaches to the new hydrogen-related infrastructural and industrial initiatives, can facilitate the transitioning to hydrogen economy.

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Appendix F

Country profile Latvia

Contents

Summary of national opportunities and challenges

Opportunities	Challenges
Large potential for excess clean electricity production	No national hydrogen strategy or roadmap
Potential to utilize forestry and agriculture biomass waste for hydrogen and hydrogen derivative production	Low degree of industrialization – little existing hydrogen production and consumption, as well as small number of workers with suitable skills
Likely to reach RED III criteria for additionality and grid carbon intensity due to growth in renewable electricity share	No infrastructure for hydrogen storage and export
Increasing need for renewable electricity consumption to avoid cannibalization	Low political ambition level regarding hydrogen
Socio-political acceptance driven by concerns over energy security and dependence	Authorities' and public's low awareness of hydrogen
	Local opposition to green iniatives
	No education programmes on hydrogen

National hydrogen strategies and targets

As of today, Latvia does not have national strategy or roadmap related to hydrogen. In the draft of Latvia's National Energy and Climate plan (NECP), a policy action is included to develop an action plan for the creation of hydrogen infrastructure and market conditions in Latvia by 2025. The Ministry of Climate and Energy and Ministry of Economics will be the main responsible authorities of the action plan. Regarding quantified hydrogen-related targets in the NECP, the plan is to install hydrogen refueling stations as specified in EU legislation, with the current proposal being to install two hydrogen refueling stations to Latvia by 2030.

Hydrogen Strategy /Roadmap
No

National networks

The Latvian Hydrogen Alliance is an open, democratic forum that unites private companies, government agencies, public organizations, universities, and research institutes involved in hydrogen technologies in Latvia. It operates without membership fees or a formal board. The Alliance includes around 50 organizations, such as the National Power Company, manufacturers, airports, ports, fuel retailers, and startups. Its main goals are to create hydrogen ecosystems, engage stakeholders, attract EU support, support Latvia's smart energy and mobility innovations (RIS3), and collaborate with state institutions to improve legislation. On November 29, 2022, most members signed a Memorandum of Understanding with the Latvian Ministry of Economics to accelerate hydrogen industry development, with the Latvian Green and Smart Technology Cluster holding the Memorandum.

The **Latvian Hydrogen Association** [1], founded in 2005, aims to advance hydrogen economics in Latvia by using local natural resources and hydrogen to support energy, transportation, and manufacturing with minimal environmental impact. Its mission is to unite scientists and business communities to explore renewable resources and address societal challenges. The Association's main goals are to accelerate progress in hydrogen technologies and research in Latvia, integrate hydrogen technology into education and promote it as an economic link between Latvia and Europe, promote hydrogen technologies for their environmental benefits and support sustainable energy consumption, and collaborate on projects with research and government facilities, participate in international projects, represent members at conferences, and educate young specialists in hydrogen technology.

Hydrogen state-of-play

Currently, there is no active large-scale commercial production or utilization of hydrogen, nor an established market for hydrogen in Latvia. There is one public hydrogen refueling station (HRS) in Riga [2], that has been built as part of EU funded project providing hydrogen for municipal trolleybuses and selling hydrogen produced from natural gas via an SMR unit for vehicles.

Existing hydrogen consumption sources	CO_2 reduction potential in fossil hydrogen production
0.067 t/a	**<1%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [3]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel [4].

Latvia is not a highly industrialized country. There are no direct fossil hydrogen replacement alternatives in the industry sector, which could be seen as low hanging fruit opportunities to foster the clean hydrogen transition. However, the absence of large energy intensive and hydrogen consuming industries can provide a good opportunity for large-scale hydrogen and hydrogen derivatives production for export needs.

Although there are no ammonia or methanol production facilities nor refineries in Latvia which could be large-scale direct fossil hydrogen replacement alternatives in the industry sector, there are existing industrial players who have a high natural gas and power consumption that could benefit from the transition to clean hydrogen. These industrial players are glass producer, cement plant, plywood and wood-based panel makers, gypsum drywall maker, municipal heating utilities and power generators, both national and local ones.

Clean hydrogen can benefit a glass manufacturing plant in Valmiera which consumes around 15 million m^3 of natural gas annually and where hydrogen could be a viable alternative for the decarbonisation. In addition, a cement maker currently uses RDF (waste), coal dust and some natural gas as an ignition pilot as primary heat source. Introducing clean hydrogen could potentially offer benefits, depending on the technological compatibility. Plywood and wooden based panel makers could potentially also substitute natural gas with hydrogen in their production processes. Gypsum drywall manufacturer is also actively looking for the alternatives for natural gas consumption in their production processes and could benefit from the (low cost) hydrogen introduction. Array of the local municipal utility (heating and combined heat and power (CHP)) operators can also be seen as potential consumers of hydrogen that is delivered at competitive cost (e.g. compared to the wood chips) or via dedicated infrastructure. A national power company is operating two large CHP units with total power capacities of 1 039 MW and 1 617 MW of heat, which are fuelled by natural gas. The company is already exploring scenarios for add-mixing clean hydrogen with natural gas to lower its greenhouse gas footprint. Introducing hydrogen in the industrial heat processes for the beforementioned manufacturing industries currently consuming natural gas as primary industrial heat source could result in a significant reduction of greenhouse gas emissions in Latvia.

Ammonia production	Refineries	Steel production
No	**No**	**No**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxis, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in

agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

Transport accounts for 31% of Latvia's energy consumption (2019). While electrification is more feasible route for decarbonisation, a minor impact if foreseen through hydrogen and e-fuels. The National Energy and Climate Plan (NECP) includes targets for purchasing electric or hydrogen trains with allocated budget. In particular, Latvian harbours have a good potential to transform into clean energy hubs at the west coast (Ventspils and Liepaja). Ventspils port has a large existing fossil energy (petroleum products, petrochemicals, ammonia) storage and handling capacity which can be beneficial for Power-to-X (PtX) products.

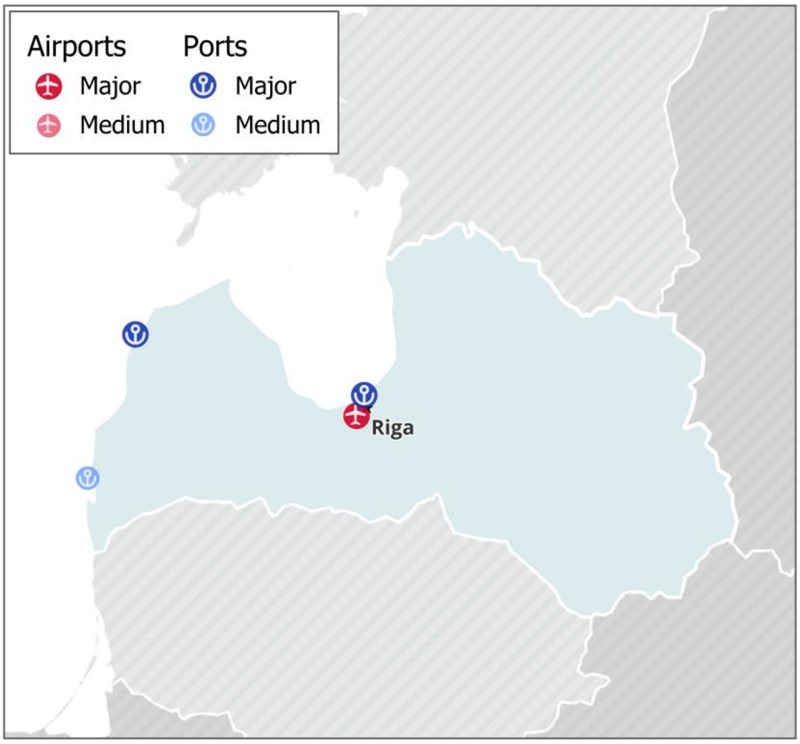

Figure 1. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) [5].

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
98%	**78% (23 ktoe)**	**2 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [6]

Hydrogen refueling infrastructure

As of today, there is one public HRS in Riga (Figure 2) that has been built as part of an EU-funded project providing hydrogen for municipal trolleybuses [2]. The HRS sells fossil hydrogen from a steam methane reforming (SMR) unit for vehicles at price of 13.17 €/kg (exlcuding VAT). The Latvian National Energy and Climate plan's draft foresees the building of two HRSs by 2030 with a funding of 10 M€.

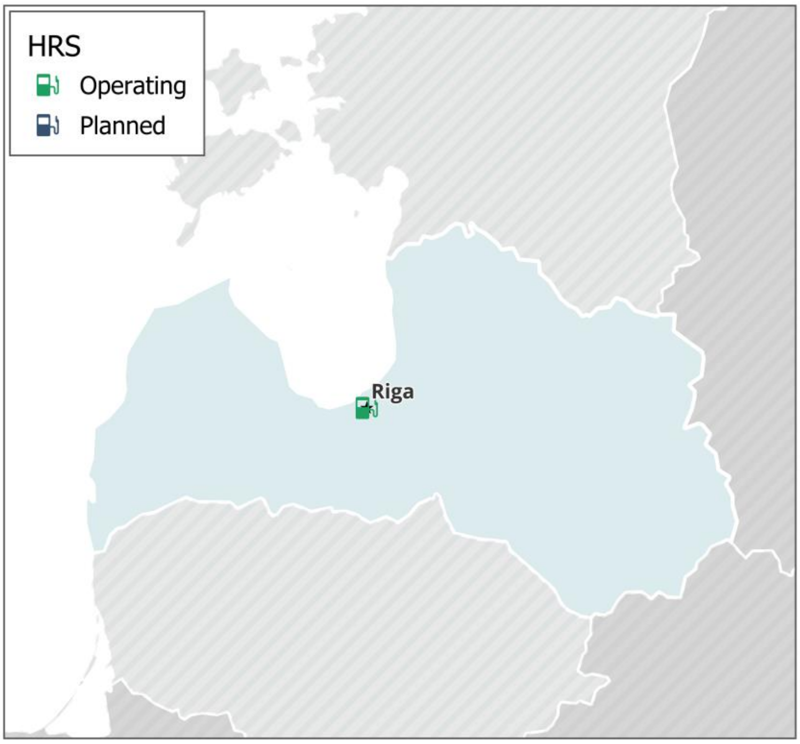

Figure 2. Operating and planned hydrogen refueling stations based on [7], [8].

Resource availability

Renewable electricity production

Latvian renewable targets are outlined in National Climate and Energy Plan 2021 – 2030 and foresee a gradual increase of the renewables share. However, there are no explicit scenarios defined to reach 100% of renewable energy production by 2050. Policy objectives to reach renewable targets might not be sufficient and are missing regarding energy storage. Although there are renewable energy projects in development, the necessity for energy conversion to energy storage solutions might be needed to alleviate the full transition from use of natural gas in power generation and a reliance on imports for energy independence. Opening up more offshore territory for wind development would support these targets and provide a good basis for energy and hydrogen exports in the future.

The recent trends in renewable electricity generation capacity in Latvia are illustrated in Figure 3. National power consumption varies around 6 – 7 TWh/a, from which around half is generated by the hydropower station cascade on the main river Daugava. From the remaining demand, half is imported via interconnections, primarily from Scandinavia and the remaining quarter is generated by two CHPs operated by Latvenergo in Riga running on natural gas.

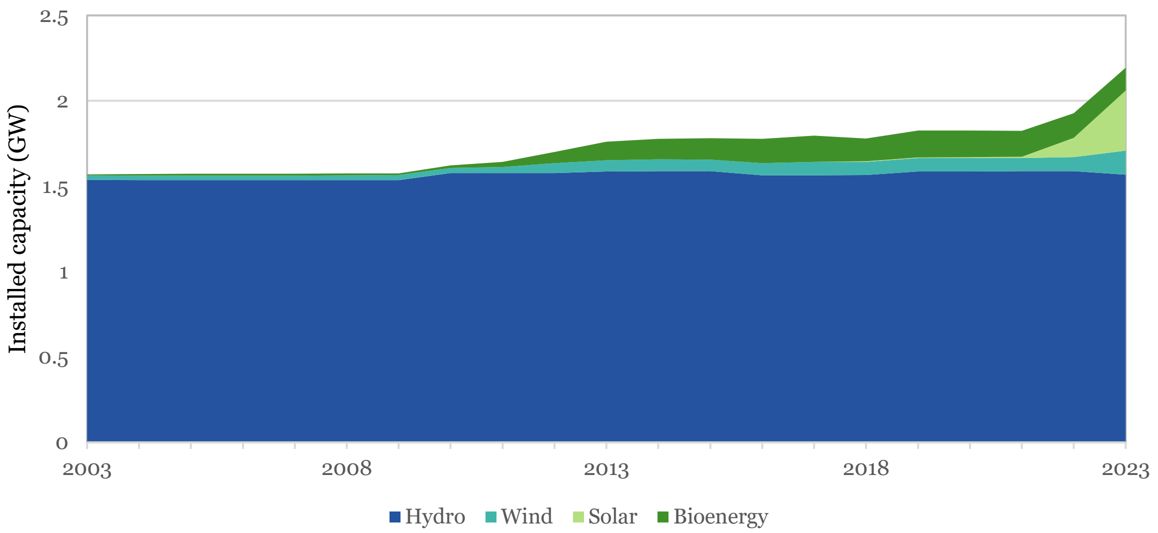

Figure 3. Renewable electricity generation capacity in Latvia between 2003-2022 [9].

Both onshore and offshore wind and solar energy are still rather undeveloped in Latvia, and with the rise of production capacities in these sectors Latvia could potentially reach 100% self-sustainable power generation with opportunity to convert excess into the hydrogen or hydrogen derivatives. The carbon intensity of the Latvian power sector was 181.82 gCO_2eq/kWh in 2022 [10]. According to the first Delegated Act (DA) [11] supplementing the recast Renewable Energy Directive 2023/2413 (RED III), the emission intensity of electricity should be lower than 18 gCO_2eq/MJ (65 gCO_2eq/kWh) in the bidding zone for the grid electricity to be classified as fully renewable in renewable fuels of non-biological origin production (RFNBO). With growth of the saturation of the renewables in the Latvian energy system, the carbon intensity of the Latvian power grid could fall below the DA threshold. In practice, this would mean that hydrogen production in Latvia could qualify as a RFNBO under the RED given that the temporal and geographical correlation, and power purchase agreement (PPA) criteria are met, thus opening opportunities for clean hydrogen production regardless of the location of the plant.

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. As for Latvia, these projects include 4.9 GW of solar energy, 7.3 GW of onshore wind energy, and 0.5 GW of offshore wind energy, totaling **12.8 GW** of new renewable electricity capacity in the pipeline (Figure 4).

Figure 4. Renewable electricity projects (GW) in the pipeline in Latvia on data collection conducted in BalticSeaH2.

Wind energy generation Latvia is currently strongly lagging the rest of the Europe, which in turn can provide an opportunity for rapid development for the onshore wind farms. Changing government policies could facilitate progress and unlock the opportunities of numerous projects that have been delayed by environmental impact assessments and building permit approval processes.

From the perspective of the hydrogen and hydrogen derivatives production many renewable energy project developers are coming to the realization that their project development will be faced with rapid price cannibalization due to high saturation of the renewables in the local energy market thus reducing profitability of the projects and delaying payback. The need to bundle project development with the electricity conversion to hydrogen and hydrogen derivates is thus increasing interest. The challenge yet is the absence of local consumption and lack of infrastructure solutions for large-scale hydrogen storage and export (e.g. pipelines, port terminals).

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 5 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

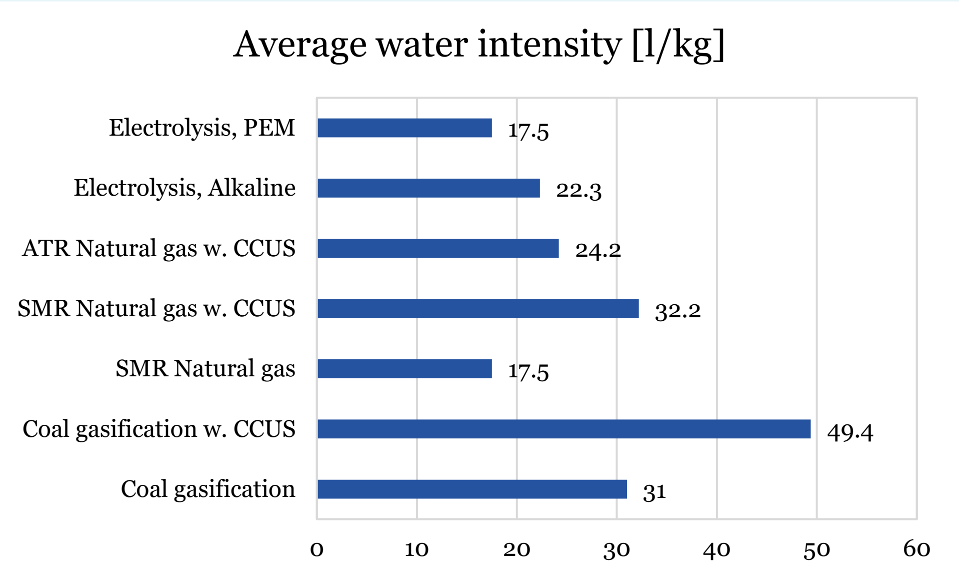

Figure 5. Average water consumption intensities by hydrogen technology [12].

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

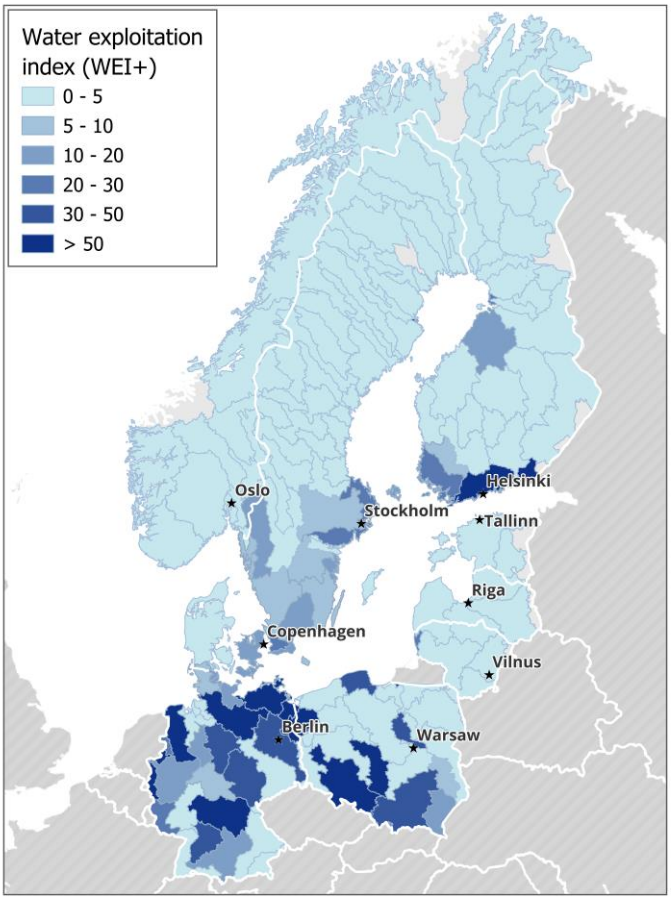

Figure 6. Regional WEI+ values for BSH2 countries in Q3, 2019 [13].

In general, Latvia does not face water scarcity at the country level, neither does it have areas that significantly differ from the national general view. The expected hydrogen projects involving water electrolysis would raise hydrogen production in Latvia by 490 kt/a, which means an extra 9.7 million m^3 of water use (assuming average use of 19,9 l/kg between PEM and AEL).

WEI+
0.39%
BSR range: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (< 0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Available CO2 in Latvia (when calculating industrial sources larger than 0,1 Mt/year) is relatively very small compared to other countries, only 1.8 Mt/year. The greatest sources of CO2 are around the cities of Saldus and Riga, but also some in between, around Jelgava (Figure 7). If the CO2 is biogenic, there could be options for power-to-x production or a CO2 hub, as the sources are quite close to each other.

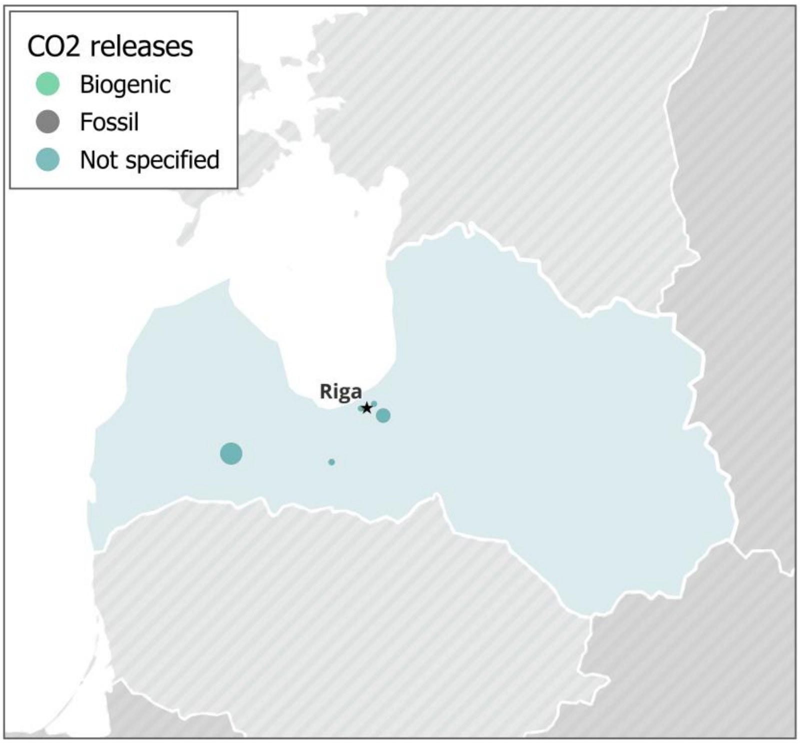

Figure 7. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [14].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

Latvia's natural gas transmission system and storage operator Conexus Baltic Grid (Conexus) manages a natural gas pipeline network of 1 190 kilometers, which is also connected to the neighboring countries. The current gas transmission system is not fully utilized and hence repurposing existing natural gas pipelines for hydrogen transmission could be an alternative in Latvia. However, greenfield hydrogen transmission pipelines are also needed. The planned location of the repurposed and newly built hydrogen transmission pipeline network for 2030 and 2040 is presented in Figure 8.

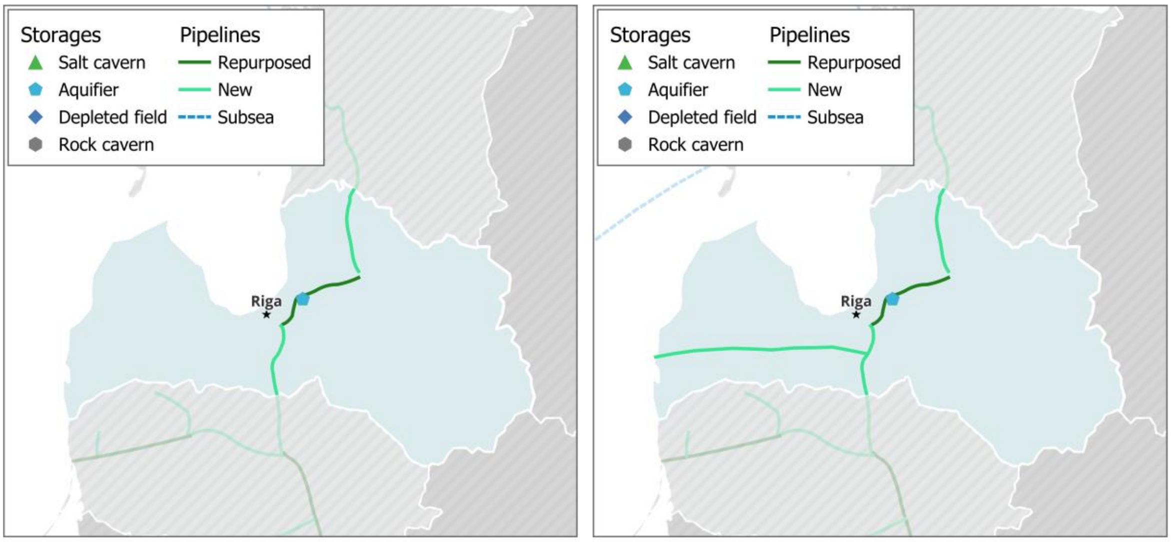

Figure 8. Left: Hydrogen infrastructure vision for 2030. Right: Vision for 2040 [15].

Together with Gasgrid, (Finland), Elering (Estonia), Amber Grid (Lithuania), Gaz System (Poland), and ONTRAS (Germany), Conexus Baltic Grid is involved in a **Nordic-Baltic Hydrogen** Corridor project (Figure 9), to establish a hydrogen transmission infrastructure between Finland, Estonia, Latvia, Lithuania, Poland, and Germany [16]. The cross-border pipeline is scheduled to become operational by 2030. Conexus Baltic Grid has also conducted a market study for the potential of hydrogen supply to the grid among local companies [17].

Figure 9. The Nordic-Baltic Hydrogen Corridor [16].

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [18]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which hydrogen is stored predominantly in salt caverns. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

Latvia has one existing natural gas aquifer storage in Inčukalns operated by the national TSO JSC Conexus Baltic Grid. There are plans to conduct a study on the adaptation of underground natural gas storage site to hydrogen storage, also outlined in the National Energy and Climate Plan (NECP) of Latvia. Additionally, similar aquifers have been identified and deemed to be potentially suitable for NG, CO2 storage and possibly H2 storage. Aquifers are at the depth of 800–1200 m and located in Western part of Latvia (Kurzeme region).

Hydrogen production plans

Currently, there is no active commercial fossil nor clean hydrogen production or utilization in Latvia, despite the fossil hydrogen produced for a refueling station in Riga. However, hydrogen projects with varying degrees of maturity are currently in development in Latvia, with total estimated electrolyzer capacity of almost **2.9 GWe**. Assuming a 65% electrolyzer efficiency and year-round operational availability, the combined planned hydrogen production capacity in Latvia is up to **350 kt/a** by 2030. It is noteworthy that the early-stage projects by project developer Purplegreen PtX, collectively account for nearly all of this capacity. The company aims to utilize hydrogen for ammonia and methanol production in Latvia. In addition, some of the early-stage projects have not disclosed any information regarding their planned production capacities or volumes and are hence excluded from this value.

In the Figure 10 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project.

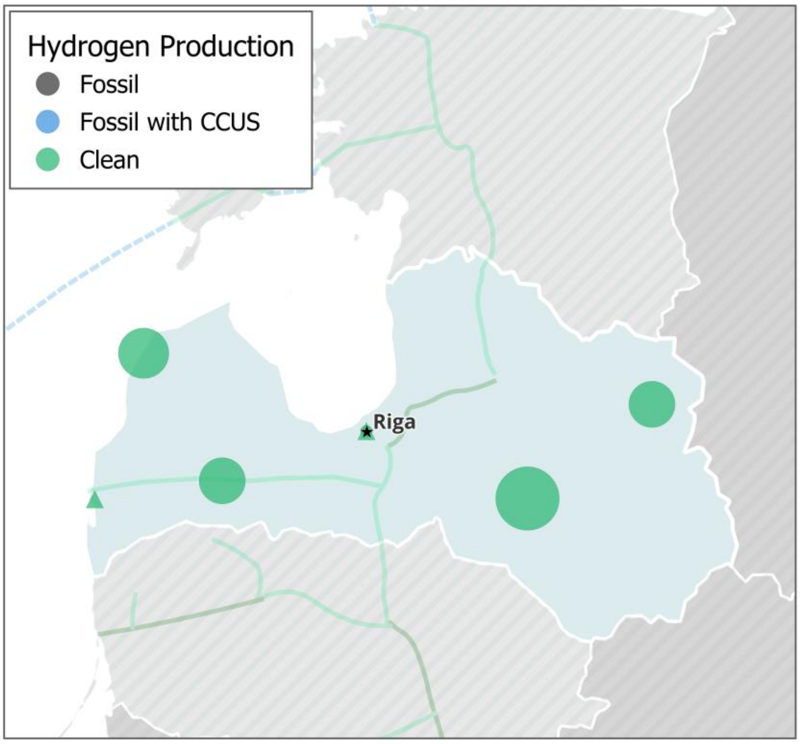

Figure 10. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

Based on public announcements, the only clean hydrogen project that has received final investment decision is the EU-funded H2Value-project, in which an environmental service company "ZAAO", as part of the project's pilot activities, is planning to obtain one hydrogen waste truck and install a small hydrogen refueling station to fuel the truck. Hydrogen will be produced in Tartu, Estonia and part of the hydrogen will shipped for consumption to Valmiera. The H2Value pilots in Estonia and Latvia will demonstrate the three phases of the hydrogen value chain.

1. Production - In Tartu, a solar plant is set up to supply power to an electrolyzer, which will convert tap water into hydrogen. The produced hydrogen will then be compressed and stored.

2. Distribution - The compressed hydrogen will be delivered to the refueling stations in Tartu and Valmiera.

3. Consumption - Two fuel-cell electric vehicles – a bus and a waste truck - will be supplied with hydrogen at the refueling stations in Tartu and Valmiera.

Early-stage hydrogen development is also taking place in Latvia's energy sector. Latvia's national power company A/S "Latvenergo" is exploring various scenarios for clean hydrogen production. Their main objective is to add-mix hydrogen with natural gas in CHP plant at the max proportion of 5%. A 15 MW electrolyzer is currently considered for piloting this initiative. In addition, the company is exploring the potential for hydrogen use in transport and synthetic fuel production to ensure economic viability. As of now, no concrete decisions have been made regarding the pilot project.

Riga's municipal heating company A/S Rīgas Siltums studies the installation of an electrolyser in one of the companies heating plants, in which CHP is running on wood chips. Excess electricity is foreseen to be used for hydrogen production, storage and usage for power generation via fuel cells to (re-)supply power for the CHP plant.

Potential geographical areas for hydrogen development

Riga region as larger agglomeration has a lot of industries, municipal utilities and transport which can provide for the full hydrogen value chain elements and better sector coupling than a smaller town. Another aspect is port and airport operations where hydrogen can find its fit. Riga internation airport along with other participants of Latvian Hydrogen Alliance last year already explored opportunities for founding of a Hydrogen Valley and applied for the Horizon Europe funding. Also, RIX airport became a partner in Interreg BSR project BSR HyAirpor in consortia led by Hamburg airport, in which integration of hydrogen technologies in airport are explored [19]. City of Riga is also close to the gas transport backbone and can benefit from the hydrogen transportation backbone development (EHB). In addition, Riga is on the route of RailBaltica project. Challenges for hydrogen deployment are with the availability of the larger scale renewable energy in the area and in particularly wind. Building wind farms near cities and villages faces limitations due to the densely populated nature of the area.

Ventspils area in particular and **Western part of Latvia** in general has a very good potential for the wind energy development, both onshore and offshore. Currently two largest onshore wind parks in Latvia to date (20.8 and 58.8 MW) are located just on the outskirts of the city with several more announced for construction. Port historically has been a hub for the trans-shipments of the fossil energy cargoes (oil, petroleum products, petrochemicals, coal, and fertilizers). Thus, there is an advantage for the production, storage, and export of the renewable fuels. There is also the only existing biorefinery in Latvia producing first generation biofuels (FAME). Challenges are that the city is relatively small (approximately 30 000 population) and has no connection to the natural gas main lines, however it is connected to two petroleum product main lines (former "Druzhba" pipeline network) which are stretching from East of the country to the West for 300 km and has a branch to the oil refinery in Lithuania (Orlen's Mazeikai refinery).

Liepaja region is located on the western coast of Latvia and can potentially benefit from the growth potential of the renewable energy (onshore and offshore wind). The city is the third largest in the country and was in the past a larger industrial center with focal point of the steel mill which has been shut down by now for the past 10 years. Industry presence and some potential in the transport sector can help for the offtake of the hydrogen thus contributing to the value chain formation. The port also has several small-scale petroleum and petrochemical export terminals which can potentially help with logistic. The city is also connected to the natural gas grid which can provide for the future opportunities with conversion to hydrogen transport.

Valmiera is home of the Latvia's and region's only glass factory (fiberglass production) which is one of hard-to-abate industries, so hydrogen can provide an alternative for natural gas there. Establishing an energy hub in the vicinity of this local small industrial cluster can potentially find also hydrogen offtake in the other industries. In addition, Valmiera is participating in cross border project with city of Tartu (Estonia) – H2Value which plans hydrogen pilot production in Tartu and hydrogen utilization in public buses transport and one hydrogen waste collecting truck operating in the Valmiera region.

Jekabpils city and region is located at the middle of the country with several larger-scale renewable energy projects planned for construction nearby. The company developing these projects is exploring PtX production opportunities. City has a small-scale industry cluster which can be helpful for the Hydrogen Valley creation and has a rail connection to the other locations, potentially enabling production and export of green ammonia to the fertilizer plant in Lithuania some 220 kilometers away.

Education and workforce skills

Currently there are no educational programs including the hydrogen technologies in Latvia, nor programs targeted for re- or upskilling of workforce.

The need for specialists in any sector related to hydrogen industry may vary depending on how fast hydrogen technologies are introduced and how much hydrogen technologies are included in the education program. Similarly, related professions such as renewable power, battery technologies or even basic power engineer or technician may lack qualified staff due to insufficient study programs and student numbers. Regions other than the capital Riga will suffer the most.

The regions with the highest unemployment rates are in Easter part of the country (Latgale) close to the border with Russia and Belarus. Currently the perspectives for hydrogen technology development there are unknown and presumingly low.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [20]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [21]. Recent survey [22] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [23]. The rise of right-wing politics and growing "greenlash" against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [23].

Another barrier potential barrier stems from a community-rejection (sometimes referred to as the NIMBY-effect, "Not In My Backyard"), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [24], [25], [26], [27], [28]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [29].

The success of this community ownership model in driving Denmark's wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [22], [23] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

Literature on the socio-political and community acceptance of hydrogen technologies is still sparse in Latvia, and a recent report indicates that awareness and interest towards hydrogen technologies is also among the lowest in Latvian in contrast to other European states [22]. This suggest that increased awareness activities and further exploration of socio-political attitudes of hydrogen are needed in the Latvian context.

Although local opposition to wind power is not as prominent in Latvia as it is in most Baltic Sea region states, some resistance has occurred: for instance, the Pāvilosta windfarm was opposed by locals due to its proximity to the local community, environmental impacts, and impacts on landscape [30]. On the other hand, recent proposal by the Latvian Defense Ministry to reserve wind power free zones near the eastern border, may create a geographical divide [31], where certain regions may benefit more from green hydrogen initiatives in terms of job creation, economic growth, and investment opportunities, while others may bear a disproportionate burden in terms of environmental degradation or displacement of existing industries.

In contrast to other EU Member States, the Latvian public is also reported to be less concerned than other EU Member States about air pollution and greenhouse gas emissions [20], which can translate to lower socio-political support for green hydrogen.

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Appendix G

Country profile Lithuania

Contents

Summary of national opportunities and challenges

Opportunities	Challenges
Hydrogen Development Roadmap with quantified targets adopted in 2024	Low public awareness of hydrogen
A significant volume of hydrogen utilized as a feedstock in ammonia production and oil refining processes	Lacks educational offering regarding hydrogen
Socio-political acceptance driven by concerns over energy security and dependence	
Decarbonising the current hydrogen production would substantially reduce Lithuania's CO2 emissions	

National hydrogen strategies and targets

A "**Lithuanian Hydrogen Sector Development Roadmap and the Action Plan for its Implementation**" [1] was published in 2022. The study provides a roadmap and an action plan for the development of the Lithuanian hydrogen sector. It emphasizes the significant role hydrogen can play in reducing the country's dependence on imported oil and natural gas. Hydrogen is identified as crucial for various industrial applications, such as in fertilizer and refinery sectors, as well as in power generation and transportation. The study suggests that the Lithuanian Ministry of Energy should take the lead in implementing this strategy. In April 2024, the Ministry of Energy adopted the **Lithuanian Hydrogen Development Roadmap for 2024-2050** [2]. The aim is that the Ministry will prepare and submit an hydrogen action plan for implementation in July 2024.

Hydrogen Strategy/Roadmap
Yes
Lithuanian Hydrogen Development Roadmap for 2024-2050 (2024)

The roadmap provides the following quantified targets for a Lithuania:

- By 2030, at least **1.3 GW** of electrolyzer capacity, expanding to **8.5 GW** by 2050, enabling annual production of 129 kt and 732 kt of clean hydrogen, respectively
    - The main anticipated demand in 2030 will be for ammonia production (82 kt), the transport sector (9 kt), and oil refining (5 kt)
    - Additionally, 33 kt of hydrogen will be exported
- At least 41% of domestic ammonia production enabled by clean hydrogen
- To begin using clean hydrogen in public transportation in at least 5 cities or secure funding opportunities to ensure that at least 30 buses providing public passenger transport services can be powered by clean hydrogen
- To install at least 10 hydrogen refueling stations, with at least one dedicated to the maritime sector

Quantified targets for hydrogen production
Yes
• 1.3 GW and 129 kt of hydrogen production by 2030 • 8.5 GW and 732 kt of hydrogen production by 2050

Hydrogen state-of-play

In Lithuania, hydrogen is utilized as a feedstock in both ammonia production and oil refining processes (Figure 1).

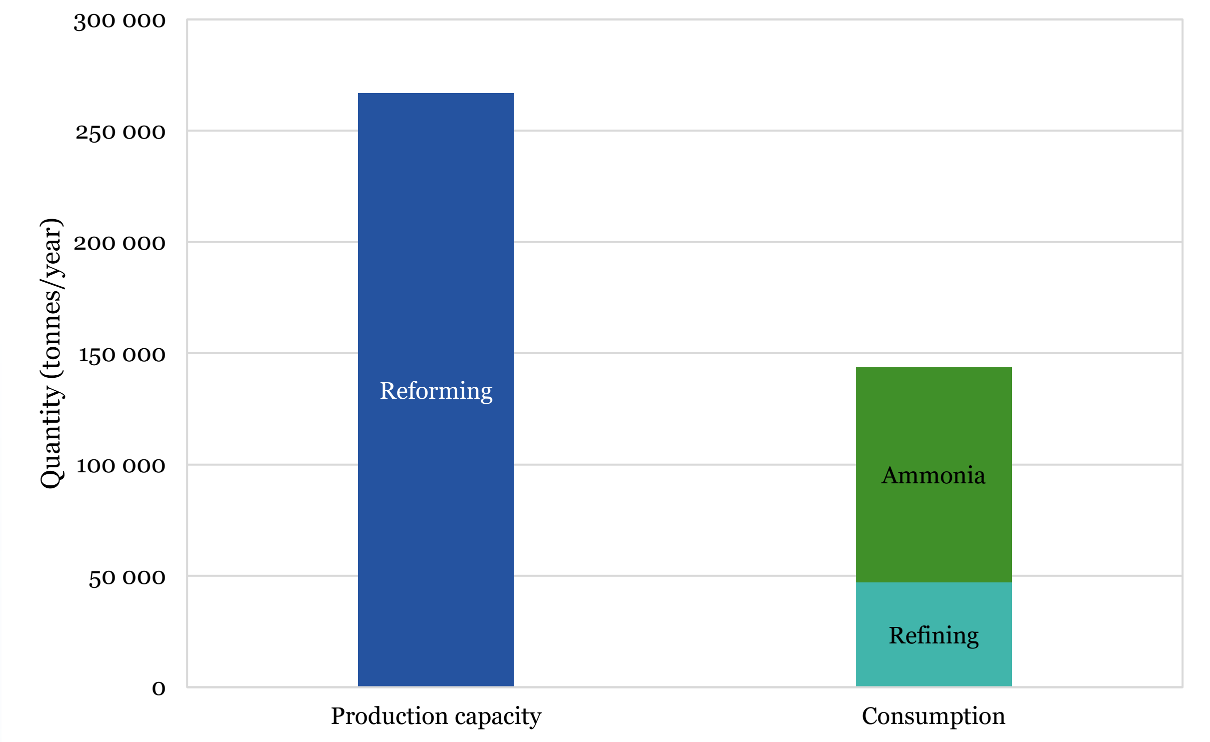

Figure 1. Hydrogen production and consumption in Lithuania [3].

The annual dedicated hydrogen production in Lithuania is approximately **267 kt/a**, all of which is produced via steam methane reforming (SMR). Assuming the carbon intensity of SMR to be 9 $kgCO_2/kgH_2$, decarbonising Lithuania's fossil-based hydrogen production would lead to 2 402 kt of CO_2 reduction, which corresponds **11.9 %** of Lithuania's total CO_2 emissions (total emissions 2021: 20 251 kt CO_2-eq excl. LULUCF [4]). The location of the operational hydrogen production facilities is presented in Figure 2.

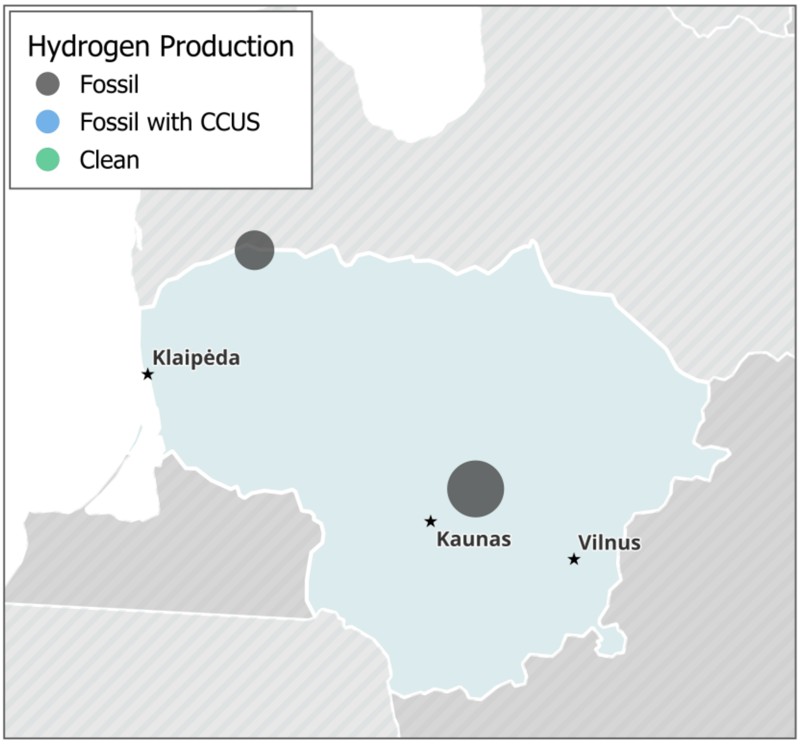

Figure 2. Operational hydrogen production facilities in Lithuania [5].

Existing hydrogen consumption sources	CO_2 reduction potential in fossil hydrogen production
145 kt/a	**11.9%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [6]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel [7].

Lithuania has two main fossil hydrogen users: one ammonia production plant by AB Achema with annual hydrogen consumption of 93 kt [8] (2022) and one oil refinery by Orlen Lietuva with capacity of 9.5 Mt of crude oil annually [9] in which fossil hydrogen could be replaced with clean alternative. Locations of these industrial plants are mapped in Figure 3. The ammonia plant produces approximately fifth of the country's greenhouse gas emissions. At the moment, these industries are finalizing their plans on how to shift their activities from fossil to clean hydrogen. Another industrial companies that can benefit from clean hydrogen are the cement and glass manufacturing plants in Lithuania (AB Panevezio stiklas and AB Akmenes cementas) that could potentially utilize clean hydrogen in providing high-temperature heat for their processes.

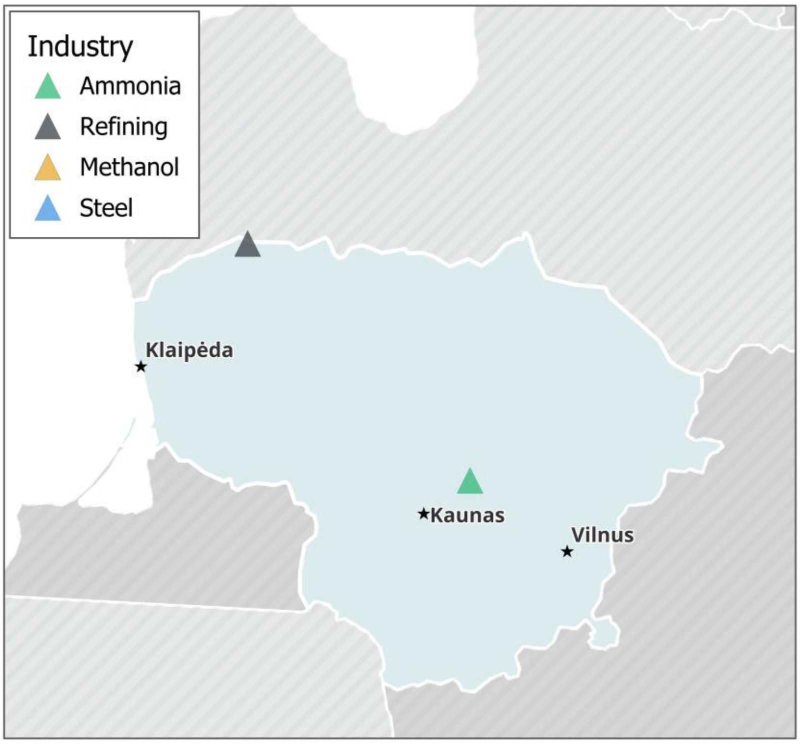

Figure 3. Locations of example industrial plants in Lithuania with potential for clean hydrogen use in decarbonisation.

Ammonia production	Refineries	Steel production
96 kt/a (hydrogen)	**9.5 Mt/a (crude oil)**	**No**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxis, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

The transport sector is responsible for approximately 30% of Lithuania's GHG emissions. With Lithuania's low population density and dispersed towns, road transport is the dominant mode of travel for both passengers and freight, making transport a particularly important sector for Lithuania's emission reduction efforts. While direct electrification is generally the most cost-efficient means to reduce emissions in the transport sector, the high reliance on road transport suggests that hydrogen could have a proportionally large share in heavy-duty road transport energy consumption in Lithuania, in comparison to other countries in the Baltic Sea region.

Klaipėda harbor is actively adopting hydrogen technologies and has the potential to become a key harbor in the Baltic Sea region, particularly in the realm of hydrogen and other alternative fuels. Furthermore, Klaipėda harbor has initiated a project to install a Hydrogen Refueling Station (HRS) and an electrolyzer. The goal is to develop this area into a leading hydrogen hub in Lithuania. The presence of an LNG terminal in the harbor positions Lithuania for potential contributions to the import or export of e-fuels in the future.

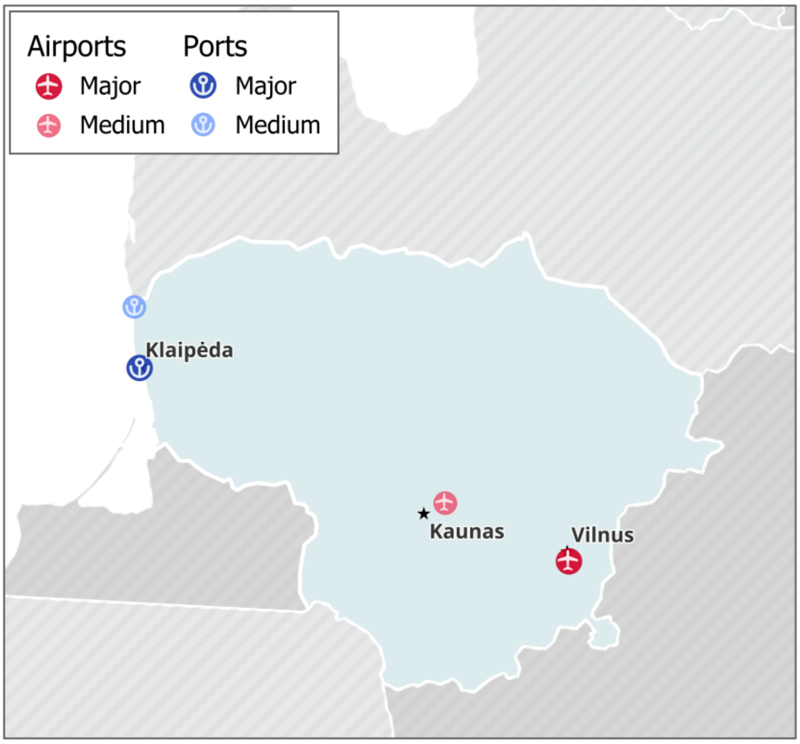

Figure 4. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) [10]. Source: Eurostat, 2024 (https://ec.europa.eu/eurostat/web/main/data/database).

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
94%	**90% (27 ktoe)**	**3 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [11]

Hydrogen refueling infrastructure

As of today, there are no hydrogen refueling stations in Lithuania (Figure 5). The Ministry of Transport and Communications in Lithuania has launched a call to develop the hydrogen refueling network in Lithuania. The plan is to install four public hydrogen refueling stations to supply hydrogen for both heavy-duty and light vehicles by 2026 with 3.6m€ of support from the Recovery and Resilience Facility (RRF) [12]. Currently, a call for the installation of public hydrogen refueling stations has been announced, with more than 2 million euros allocated for this purpose. Applications are being accepted until July 10, 2024. The total target of the Ministry of Transport and Communications in Lithuania is to install at least 10 public and private hydrogen refueling stations by 2030.

A public hydrogen refueling station is planned to be built to the Port of Klaipėda in 2026 as part of a 2-year EU-funded project “Developing the production of green fuels (hydrogen) in the Port of Klaipėda” [13]. The produced hydrogen is planned to be used in the public transportation in the region.

In addition, Vilnius, Lithuania's capital, has given green light to foster the production clean hydrogen and integrating it into the city's transportation network [14]. An important element in this initiative is the aim to purchase 16 hydrogen-powered buses to replace conventional diesel buses. The clean hydrogen would be derived from a 3 MW electrolyzer that will be integrated with the district heating network of Vilnius. Based on the estimation, the electrolyzer could supply hydrogen for 40 buses. The hydrogen-fuelled buses are planned to be introduced in 2026.

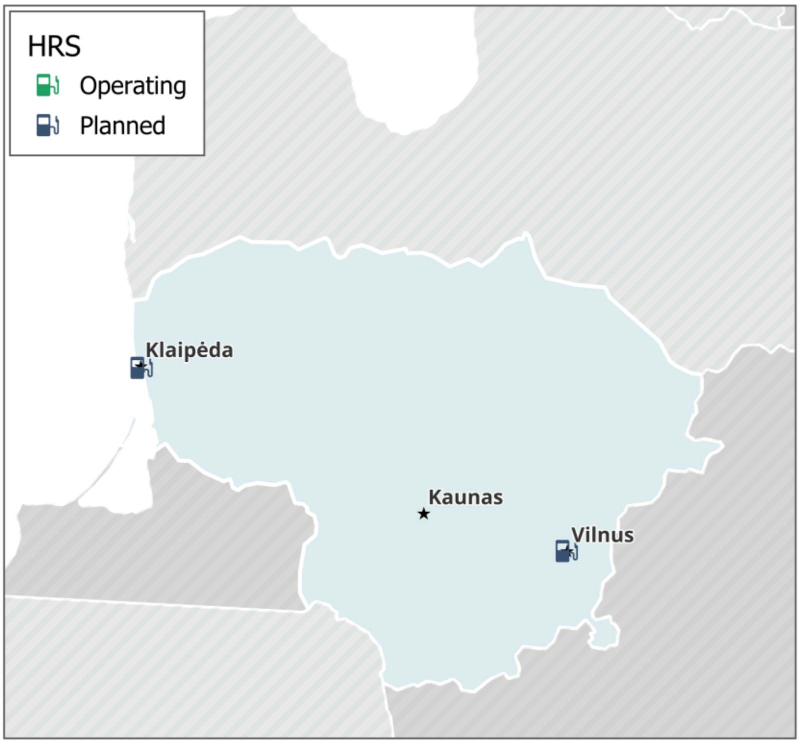

Figure 5. Operating and planned hydrogen refueling stations [15], [16] and publicly announced projects.

Resource availability

Renewable electricity production

In 2022, Lithuania consumed 11.2 TWh of electricity, while the country's overall electricity production reached 4.25 TWh, accounting for 37% of Lithuania's total demand. To enhance cost efficiency, a significant portion of Lithuania's electricity is imported from Scandinavia, primarily Sweden, and other Baltic countries. In 2022, renewable energy power plants in Lithuania contributed to 60% of the nation's total electricity production. The total energy generated from renewable sources for the year amounted to 2.54 TWh, with solar power contributing 0.27 TWh, wind power contributing 1.51 TWh, and hydropower contributing 0.46 TWh. Lithuania's energy network incorporated four lithium-ion batteries with a combined capacity of 200 MW and 200 MWh, constituting one of the largest projects of its kind in Europe. This integration serves as an instantaneous electricity reserve in isolated mode, bolstering the security and operational capability of Lithuania's energy system.

Significant growth in wind and solar will be needed to decrease the reliance on electricity imports and to phase out generation from natural gas. Projected plans for solar, onshore and offshore wind are ambitious and hydrogen production will become feasible once renewable capacity is developed beyond domestic consumption (likely when offshore wind farms are operational in the 2030s). As the country currently generates approximately 37% of the total electricity demand, the primary focus should be on augmenting overall energy generation, with a particular emphasis on renewable sources. The insufficient capacity in renewable energy can potentially constrain the realization of large-scale clean hydrogen projects. The recent trends in renewable electricity generation capacity in Lithuania are illustrated in Figure 6.

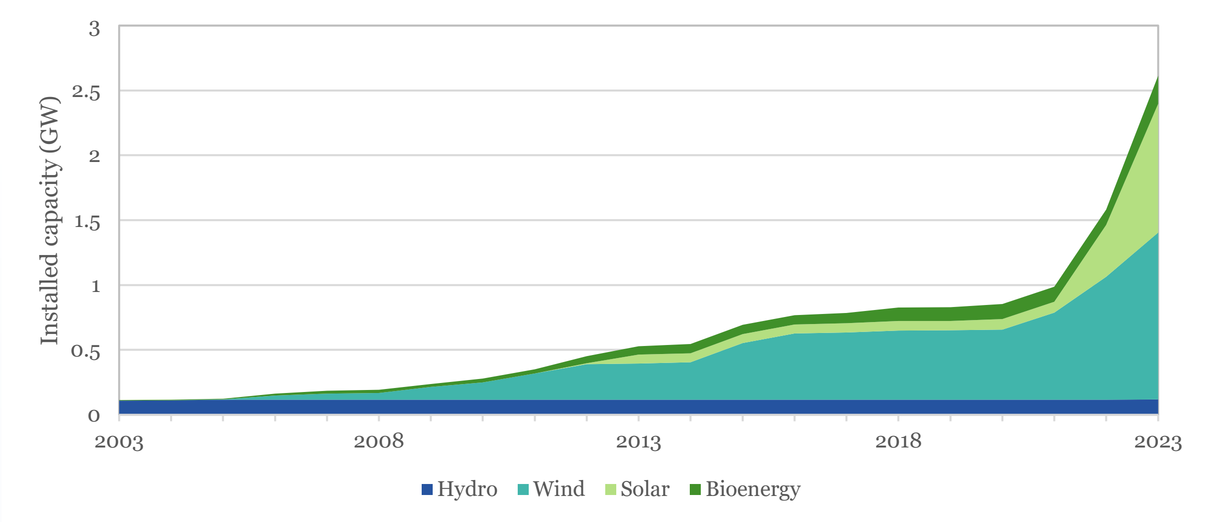

Figure 6. Renewable electricity generation capacity in Lithuania between 2003-2022 [17]. Source: IRENA, 2023.

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. These projects include 3.5 GW of solar energy, 2.7 GW of onshore wind energy, and 1.4 GW of offshore wind energy, totaling **7.6 GW** of new renewable electricity capacity in the pipeline (Figure 7).

Figure 7. Renewable electricity *projects (GW) in pipeline in Lithuania on data collection conducted in BalticSeaH2.*

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 8 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

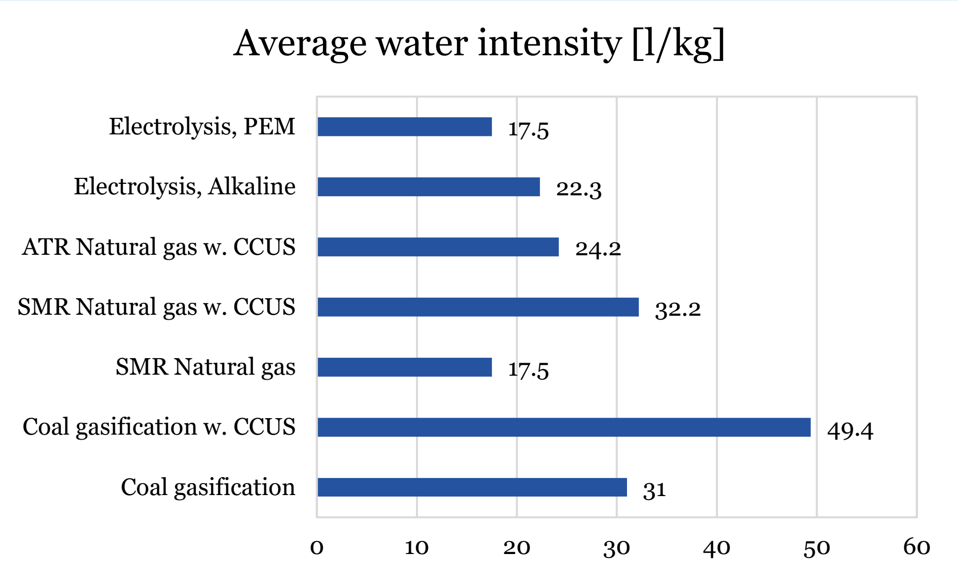

Figure 8. Average water consumption intensities by hydrogen technology [18].

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

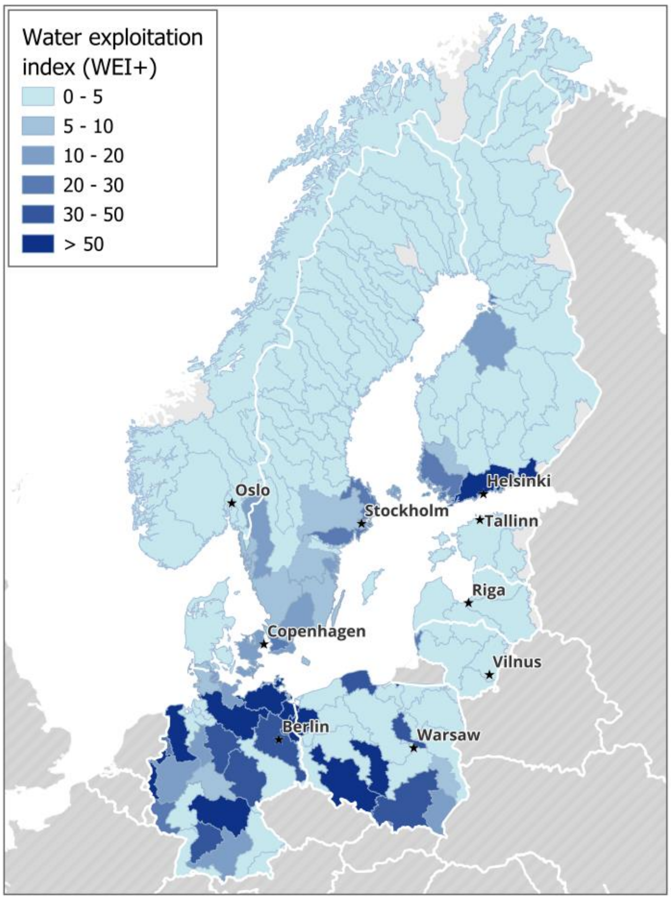

Figure 9. Regional WEI+ values for BSH2 countries in Q3, 2019 [19].

Overall, Lithuania does not have issues with water availability at the national level, nor does it have regions that deviate significantly from the national average. The projected hydrogen projects that use water electrolysis would increase hydrogen production in Lithuania roughly by 37 kt/a, which implies an additional 0.7 million m^3 of water consumption (assuming an average of 19,9 l/kg between PEM and AEL).

WEI+
0.66%
BSR range: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (< 0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Annual CO2 availability of CO2 in Lithuania is relatively small, 7 Mt/year (when calculating industrial sources larger than 0,1 Mt/year). The greatest CO2 source is in central Lithuania, around the city of Jonava, quite close to Kaunas (Figure 10). Other significant sources are in the North or Northeast, and there could thus be potential for synergies. These locations could be options for possible Power-to-X production if the CO2 originates from biogenic sources.

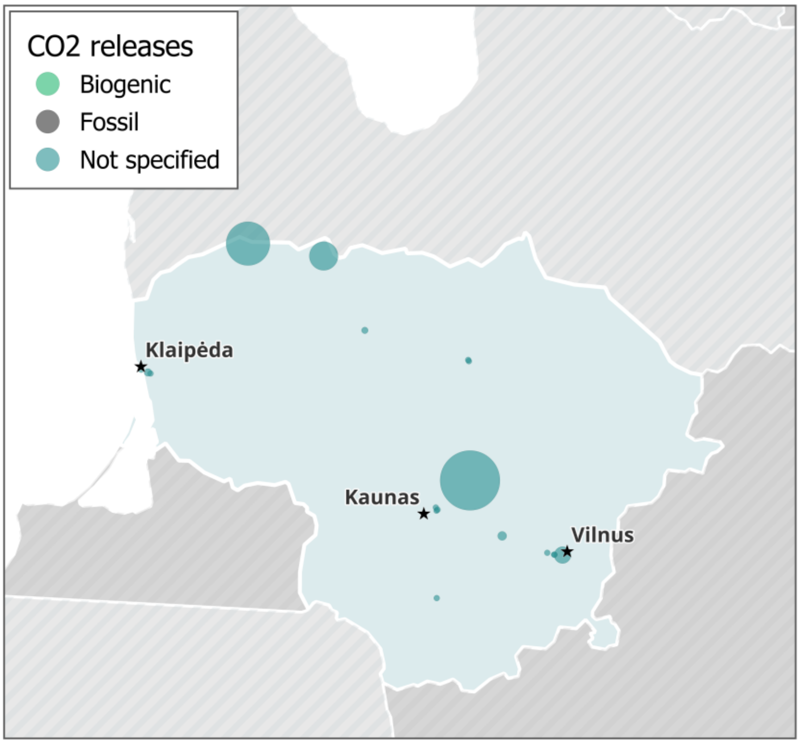

Figure 10. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [20].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

The Lithuanian gas transmission system operator Amber grid operates a 2 285 km natural gas transmission system in Lithuania. The hydrogen transmission infrastructure in Latvia is expected to consist of both repurposed natural gas pipelines and newly built hydrogen transmission pipelines. The initial stage of the hydrogen transmission network will be in the central region of the country where fertilizer production is already present. Then, the network will extend to the northwest of the country to connect with oil refineries [21].

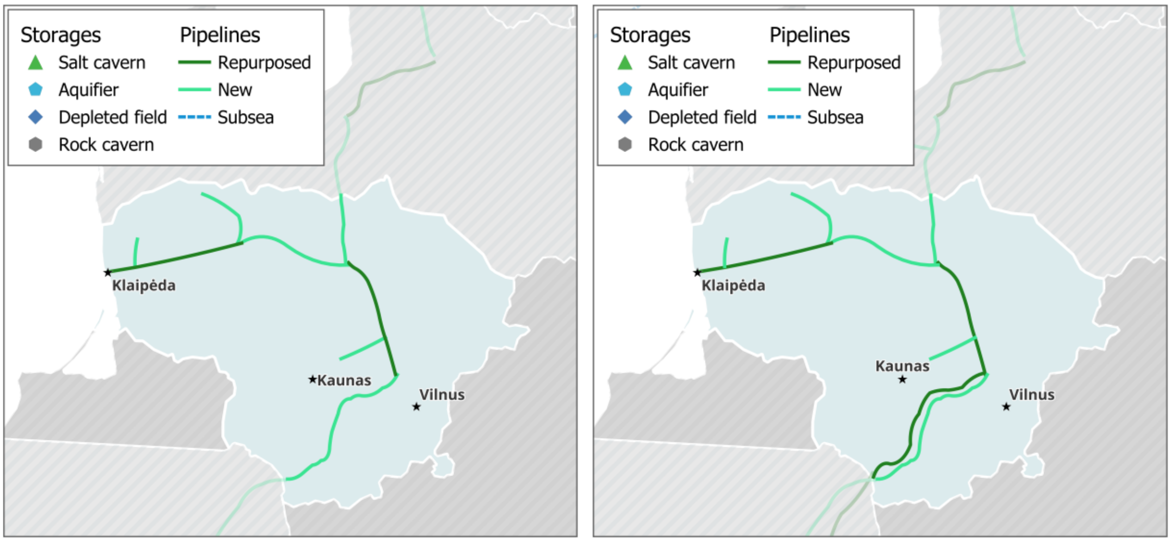

Figure 11. Left: A European hydrogen infrastructure vision for 2030. Right: Vision for 2040 [22].

As for cross-border hydrogen transmission, together with Gasgrid, (Finland), Elering (Estonia), Conexus Baltic Grid (Latvia), Gaz System (Poland), and ONTRAS (Germany), Amber Grid is involved in a **Nordic-Baltic Hydrogen Corridor** (Figure 11) project, to establish a hydrogen transmission infrastructure between Finland, Estonia, Latvia, Lithuania, Poland, and Germany [23]. The cross-border pipeline is scheduled to become operational by 2030.

Figure 12. The Nordic-Baltic Hydrogen Corridor [23].

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [24]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which hydrogen is stored predominantly in salt caverns. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BalticSeaH2 countries apart from a test facility in Sweden.

There is no underground hydrogen nor natural gas storage capacity in Lithuania. A bidirectional pipeline provides Lithuania with access to Inčukalns natural gas storage in Latvia, and uninterrupted gas supply is secured through Inčukalns connection and LNG facility in Klaipeda. As geological formations suitable for UHS are few, and hydrogen production and consumption are highly concentrated in two facilities, increasing hydrogen storage capacity in Lithuania does not take high priority.

Hydrogen production plans

Lithuania has two major companies that use fossil hydrogen as a feedstock for fertilizer and oil refining industries, which both are finalizing their plans how to shift their activities from fossil to clean hydrogen. The largest hydrogen producer and consumer in Lithuania, a fertilizer producer Achema, currently generates fossil hydrogen through steam reforming. Achema aims to produce 30% of the required hydrogen via electrolysis (213 MW) by 2029, utilizing green electrical energy sourced from an onshore wind farm (248 MW).

Based on public information, two hydrogen projects have received funding in Lithuania:

- The Vilnius City Council has approved plans to produce and use clean hydrogen in public and private transportation [25]. The city plans to buy 16 hydrogen buses to replace the diesel ones. Waste heat from hydrogen production will be used in local district heating. A 3 MW electrolyzer will start hydrogen production in 2026. The total value of the project is 8.1 million euros, with 70 percent funded by the Ministry of Energy and the rest by the city.

- A public hydrogen refueling station is planned to be built to the Port of Klaipėda in 2026 as part of a 2-year EU-funded project "Developing the production of green fuels (hydrogen) in the Port of Klaipėda" [13]. The produced hydrogen is planned to be used in the public transportation in the region.

The planned projects are shown on a map in Figure 13, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project.

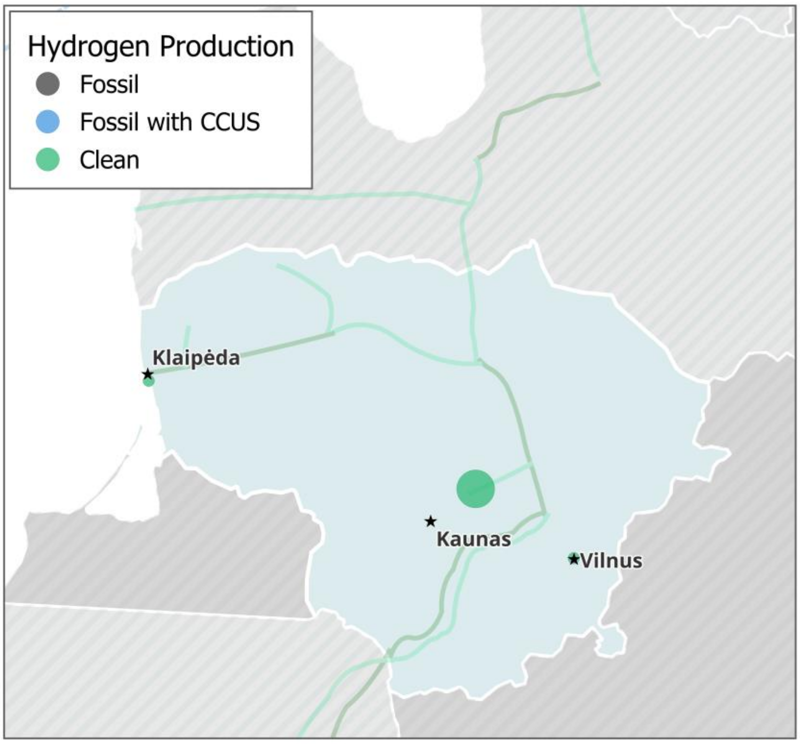

Figure 13. Announced hydrogen production plans (excluding fossil-based production).

Potential geographical areas for hydrogen development

In the **Klaipėda district**, a harbor has initiated a project to install a Hydrogen Refueling Station (HRS) and an electrolyser. The goal is to develop this area into a leading hydrogen hub in Lithuania.

Elektrėnai city aligns with the guidelines for Lithuanian hydrogen strategy, envisioning the establishment of a Hydrogen Valley in Lithuania, thanks to its conducive infrastructure.

The northern part of Lithuania is identified in accordance with the guidelines for Lithuanian hydrogen strategy as a crucial area, owing to its substantial potential for the installation of wind farms.

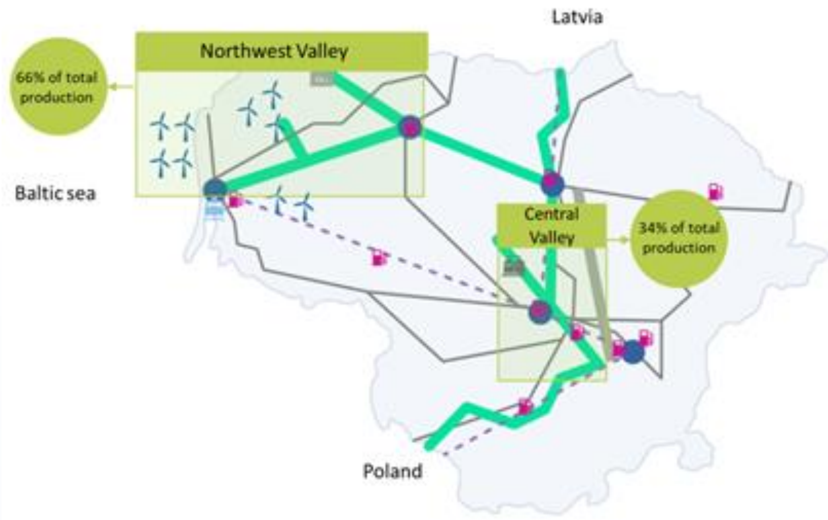

Figure 14. Potential green hydrogen production and consumption centers in Lithuania (including HRS) [2].

Education and employment

As of now, Lithuania lacks dedicated educational programs or courses centered on hydrogen. While Vytautas Magnus University and Kaunas University of Technology previously offered such courses, a decline in student enrollment and interest led to the discontinuation of these programs.

Center for Hydrogen Energy Technologies at the Lithuanian Energy Institute offers a hydrogen energy technology training program (26 academic hours) tailored for the Lithuanian industry interested in the hydrogen sector.

Within companies, not many individuals have robust knowledge about hydrogen technologies at the moment. The country still does not proactively invest in educational programs, training initiatives, and partnerships with industry stakeholders to build a skilled workforce capable of contributing to the emerging hydrogen economy.

As the adopted Lithuanian Hydrogen Development Roadmap states, one of the priorities is the development and implementation of new hydrogen technologies in Lithuania, as well as the production and export of hydrogen and its derivative technology components. Targeted funding will be allocated for research and experimental development of green hydrogen technologies, as well as for the creation of innovations and more efficient and economical methods for green hydrogen production and utilization. In order to effectively utilize funds allocated for research and experimental development, up to 5 potential areas of hydrogen research will be identified, and efforts will be made to ensure the necessary funding.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [26]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [27]. Recent survey [28] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [29]. The rise of right-wing politics and growing “greenlash” against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [30].

Another barrier potential barrier stems from a community-rejection (sometimes referred to as the NIMBY-effect, “Not In My Backyard”), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [28], [30], [31], [32], [33]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [34].

The success of this community ownership model in driving Denmark’s wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [28], [29] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

Literature on the socio-political and community acceptance of both hydrogen and other green technologies (e.g. solar, wind) is still sparse in Lithuania. Regarding climate and energy attitudes in general, Lithuania (like other Baltic states) represents a “controversial combination of rapidly increasing climate change impacts and moderate or low concern with the climate crisis”. Furthermore, while wind, solar, and nuclear power enjoy rather high public support in Lithuania, environmental concern is not a particular driver for the support. Rather, stronger drivers seem to be energy dependency and security, as a vast majority of the public view that the Ukrainian war makes it more urgent to invest in renewable energy [26].

It seems that Lithuania has not faced strong local opposition to wind power, unlike Finland, Sweden, Germany, and Norway. However, the situation can change, as the country is moving forward on a fast pace towards the instalment of a vast amount of solar and wind farms. Since the lack of cooperation and consultation with local communities, and poor technology-place fits have fuelled local opposition towards wind and solar farms, and other green initiatives (e.g., green steel mills) in other parts of the Baltic Sea region, hydrogen-related initiatives in Lithuania should proactively promote cooperation with municipalities and local communities.

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Appendix H

Country profile Poland

Contents

Summary of national opportunities and challenges

Opportunities	Challenges
Socio-political acceptance driven by concerns over energy security and dependence	Heavy reliance on coal for electricity production
Existing significant volume of hydrogen utilized as a feedstock for ammonia production and within the refining sector	Legislation not encouraging building onshore wind farms
High public support for wind and nuclear power	Significant political influence of the coal sector impacting attitudes towards the green transition
Quantified targets for hydrogen production in the Polish Hydrogen Strategy	
Suitable geological formations for large-scale hydrogen storage	

National hydrogen strategies and targets

The **Polish Hydrogen Strategy** until 2030, with perspective until 2040 [1], by the Ministry of Climate and Environment, published in 2021, defines the main goals for the development of hydrogen economy in Poland and the actions to achieve them. The Polish strategy aims to accelerate the decarbonization of the most energy-intensive sectors. It supports all methods of low-emission hydrogen production, with a focus on electrolysis, gasification, fermentation, pyrolysis, steam reforming of biogas and biomethane, as well as steam methane reforming (SMR) and coal gasification with carbon capture and storage (CCS) or carbon capture and utilization (CCU).

Hydrogen Strategy/Roadmap
Yes
Polish Hydrogen Strategy (2021)

The strategy has six goals with specific targets:

1) **Implementation of hydrogen technologies in the power and heating sector** - with research and development until 2028 and implementation in 2030
2) **Use of hydrogen as an alternative fuel for transport -** By 2025, 100 to 250 zero-emission buses powered by hydrogen are expected to be in operation, at least 32 hydrogen refueling stations will be built; the perspective of 2030 about 800-1000 hydrogen buses should be in operation
3) **Supporting the decarbonization of industry** – by 2030, at least 5 hydrogen valleys, understood as centers of excellence for the implementation of the hydrogen economy, sector integration, industry climate transformation, and infrastructure construction, are planned
4) **Hydrogen production in new installations** - to provide the conditions for launching hydrogen production facilities from low- and zero-emission sources by 2030. Planned green hydrogen production targets are 50 MW by 2028 and 2 GW by 2030
5) **Efficient and safe hydrogen transmission, distribution and storage**
6) **Creating a stable regulatory environment** - to remove barriers to the development of the hydrogen market and encourage a gradual increase in the use of RES for electrolysis

Quantified targets for hydrogen production
Yes
•50 MW electrolyzer capacity (2028) •2 GW electrolyzer capacity (2030)

National networks

Several Hydrogen Valley associations and local clusters have been initiated in Poland to foster regional hydrogen development:

- Łaszczyński Brothers Central Hydrogen Cluster

- Lower Silesian Hydrogen Valley
- Mazovian Hydrogen Valley
- Western Pomeranian Hydrogen Valley
- Wielkopolska Hydrogen Valley
- Silesian-Malopolska Hydrogen Valley
- Sub-Carpathian Hydrogen Valley
- Pomeranian Hydrogen Valley
- Mazovian Hydrogen Valley
- Lublin Hydrogen Cluster

A list of hydrogen valley cooperatives in Poland can be found from H2 Poland portal [2].

Hydrogen state-of-play

In Poland, a significant volume of hydrogen is already utilized as a feedstock for ammonia production and within the refining sector (Figure 1). The hydrogen is derived from fossil sources and is primarily generated by the end-users themselves. As a result, there is no distinct hydrogen market in Poland. The substantial production of fossil-derived hydrogen presents opportunities for decarbonization.

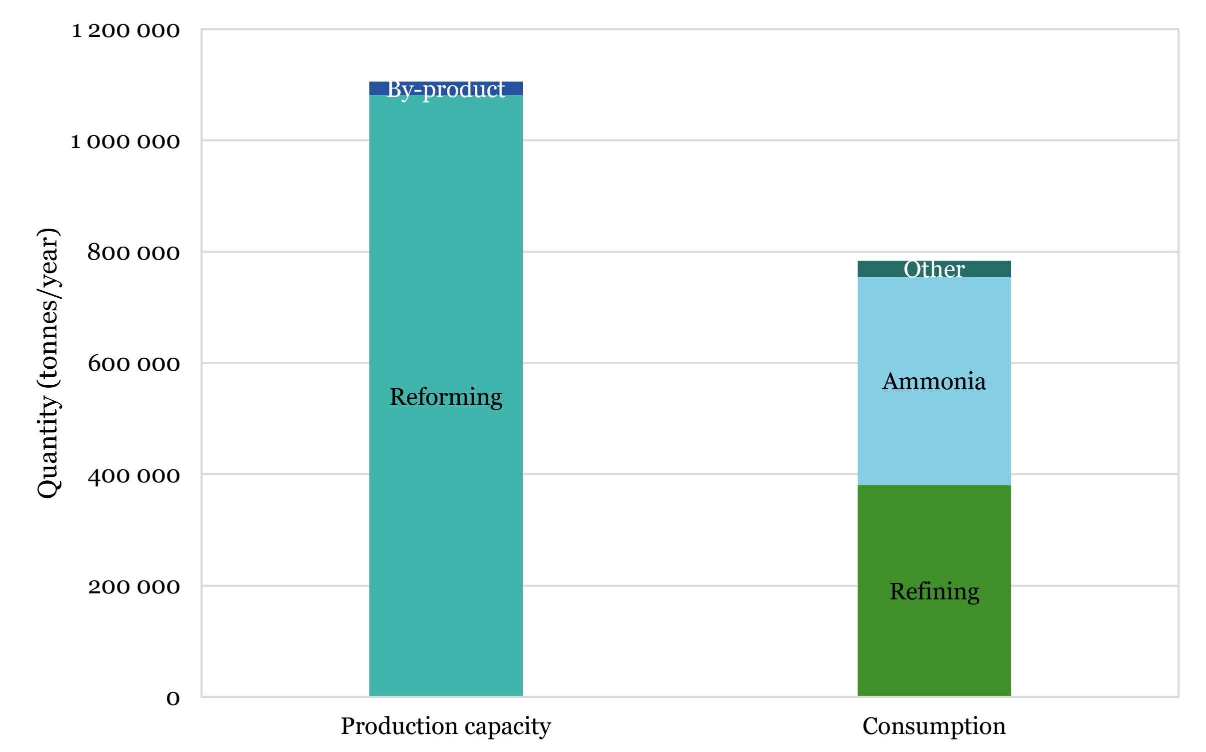

Figure 1. Hydrogen production and consumption in Poland [3].

The annual dedicated hydrogen production in Poland is approximately **1 082 kt/a**, of which all is based on steam methane reforming (SMR). Assuming the carbon intensity of steam methane reforming (SMR) to be 9 kgCO2/kgH2, decarbonizing Poland's fossil-based hydrogen production would lead to 9735 kton of CO2 reduction, which corresponds 2.4 % of Poland's total CO2 emissions (total emissions 2021: 399 438 kton CO2-eq excl. LULUCF [4]). The location of the operational hydrogen production facilities is presented in Figure 2.

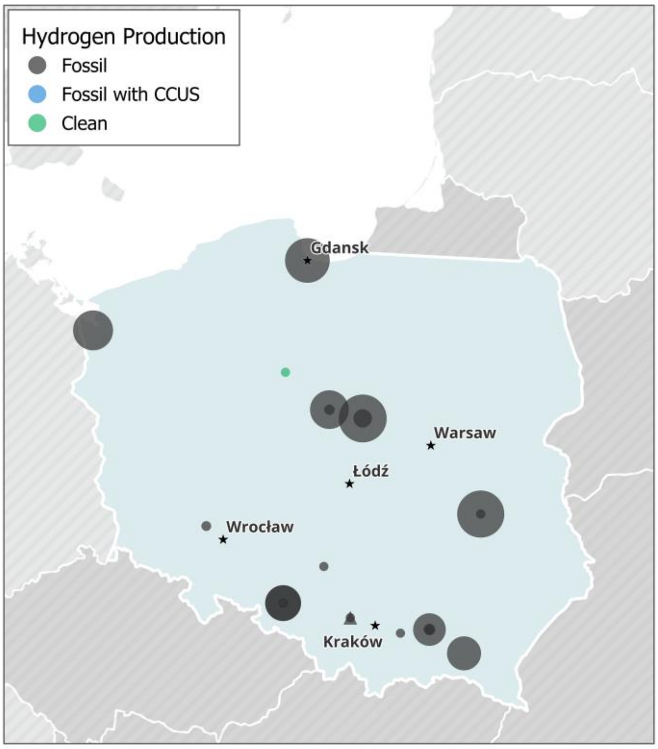

Figure 2. Operational hydrogen production facilities. Facilities with unspecified capacity indicated by triangle markers [5].

Existing hydrogen consumption sources	CO_2 reduction potential in fossil hydrogen production
784 kt/a	**2.4%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [6]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel [7].

Refining and ammonia production are the main industry sectors that already utilize hydrogen in Poland. There are five ammonia production facilities in Poland with annual hydrogen consumptions of 134 kt, 87 kt, 65 kt, 57 kt and 31 kt (2022) [8]. In addition, there are four refineries with capacities of 20 Mt, 10.8 Mt, 0.4 Mt and 0.1 Mt of crude oil annually [9] in which fossil hydrogen could be replaced with a clean alternative. The current large-scale production and consumption of fossil hydrogen creates possibilities for industrial decarbonisation in Poland. As hydrogen is primarily generated by the end-users themselves, the large industries and their decarbonization plans can be a key driver for the national clean hydrogen transition. Several of the industry companies already using hydrogen such as Orlen, are ready to invest to green transition and to reduce their carbon dioxide emissions via hydrogen.

As for the new industrial applications for clean hydrogen, Poland has two primary steel production sites with annual steel production capacities of 5 000 and 2 600 kt/a [10], in which hydrogen could be used as a decarbonisation pathway. However, this would require significant changes in the entire production process. Locations of these example industrial plants in Poland with potential for clean hydrogen use in decarbonisation are mapped in Figure 3.

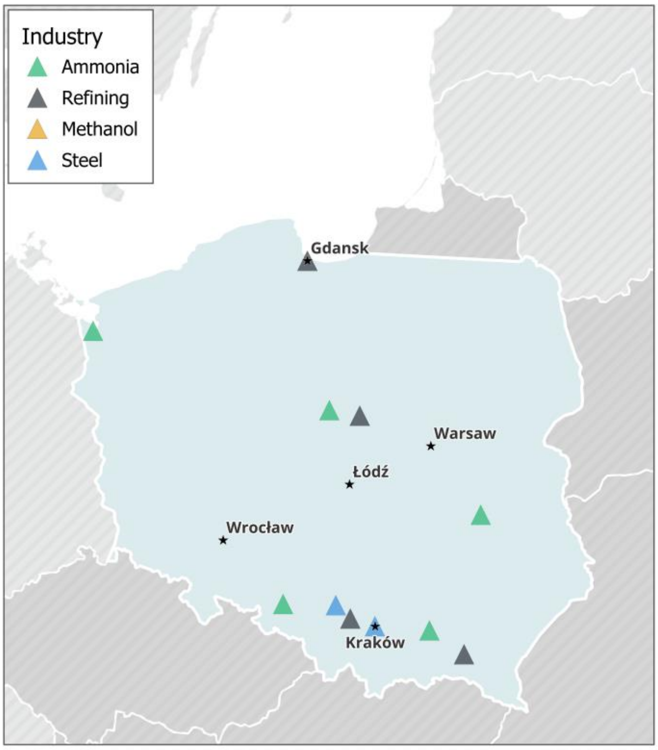

Figure 3. Locations of example industrial plants in Poland with potential for clean hydrogen use in decarbonisation.

Ammonia production	Refineries	Steel production
374 kt/a (hydrogen)	**31.3 Mt/a (crude oil)**	**7 600 kt/a (steel)**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxes, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

Fossil fuels still make up a large proportion of road transport in Poland (95%) The Polish Hydrogen Strategy until 2030 sets the use of hydrogen in transport as one of the main goals, where hydrogen is seen as a way to lower emissions in transport, especially in urban transport (buses), road transport (heavy and long-distance transport), light fleet vehicles (forklifts, vans, cabs), non-electrified rail (where electrification is not a viable option), maritime and river transport, and in the longer term also in aviation, including unmanned vehicles (drones). Hydrogen will be an alternative for those transport sectors where electrification is not feasible or possible. By 2025, there should be 100 to 250 hydrogen-powered zero-emission buses in service. At the same time, the first vessels and hydrogen trains and locomotives with hydrogen propulsion systems will start to be developed. In the view of 2030, about 800-1000 hydrogen buses should be in service, gradually replacing combustion vehicles. A network of refuelling stations will keep expanding and production of hydrogen-based fuels will start (such as ammonia or methanol). [1]

Solaris, a Polish bus manufacturer, manufactures hydrogen buses at their plant in west-central Poland. Solaris Urbino 12 hydrogen buses have not yet been deployed in Poland, but they are operating in Germany and the Netherlands. Hydrogen buses produce no emissions while in operation, and can be filled up in minutes, which provides time savings in charging compared to electric buses [11].

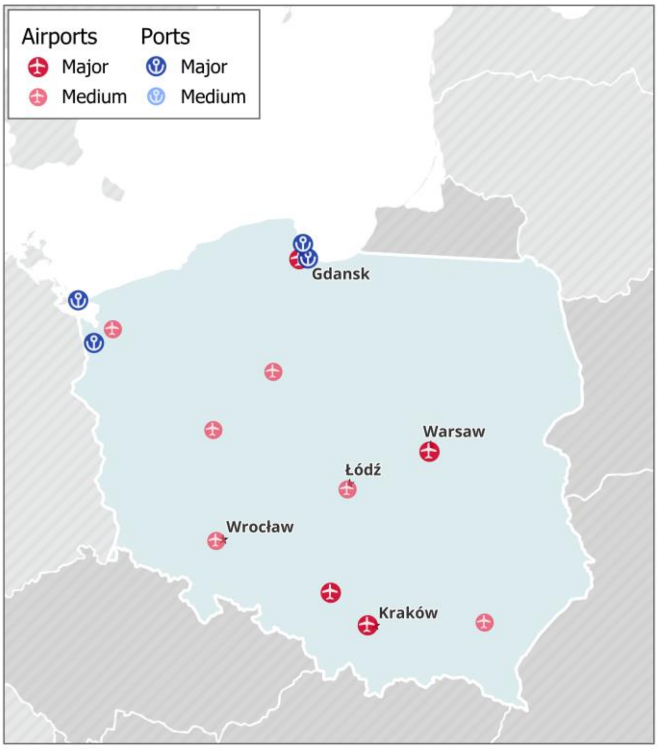

Figure 4. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) [12].

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
95%	**24% (90 ktoe)**	**1 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [13]

Hydrogen refueling infrastructure

There are six existing hydrogen refueling stations in Poland, and 13 new are being planned [14] (Figure 5).By 2025, at least 32 hydrogen refueling stations are to be built.

An important player in the Polish hydrogen transport sector is an oil company ORLEN, which plans to construct a hydrogen refueling network of 100 stations for both heavy-duty and passenger vehicles and also for rail transport in Poland, the Czech Republic and Slovakia, with 57 of the stations located in Poland [15]. The company has also piloted hydrogen-fueled locomotives for rail transport, and ORLEN and Polish rail company LOTOS Kolej intend to switch their locomotive fleet to run on hydrogen.

Figure 5. *Operating and planned hydrogen refueling stations based on* [16], [17] *and publicly announced projects.*

Resource availability

Renewable electricity production

Poland has traditionally relied heavily on coal for energy production. In recent years, there has been an increasing focus on diversifying the energy mix to include more renewable sources and gradually phase out of fossil fuels. The country has set ambitious targets to increase the share of renewables in its energy mix, aiming to reduce dependence on coal and mitigate environmental impacts. Nuclear (mainly SMRs) and offshore wind have been identified as key contributors to Poland's renewable energy portfolio.

However, the transition has some challenges. As said, Poland is extremely reliant on coal for its energy production. Therefore, the coal sector is a major employer, with significant political influence and is hence impacting attitudes towards the green transition. In addition, current legislation does not encourage building onshore wind farms as the legislation states that turbines cannot be within 700 m of any building. Furthermore, grid connections are a limiting factor for many decentralized renewable electricity projects, as the system was designed for large fossil fuel generation plants that are connected to the transmission network.

As for the development of variable renewable electricity, increased focus has been on the development of offshore wind farms as a solution. The recent trends in renewable power generation capacity in Poland are illustrated in Figure 6. As can be seen, solar power has had the most rapid expansion in recent years.

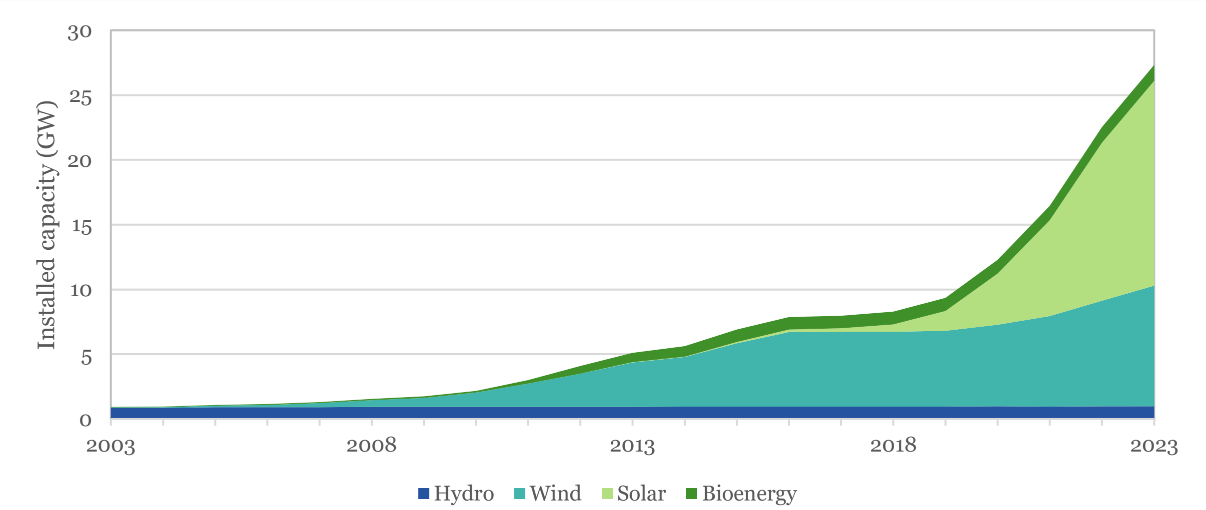

Figure 6. Renewable power generation capacity in Poland between 2003-2022 [18].

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. For Poland, these projects include 4.3 GW of solar energy, 1.2 GW of onshore wind energy, and 17.7 GW of offshore wind energy, totalling **23.2 GW** of new renewable energy capacity in the pipeline (Figure 7), with vast majority of the projects being offshore wind energy projects.

Figure 7. Renewable electricity projects (GW) in pipeline in Poland based on data collection conducted in BalticSeaH2.

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 8 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

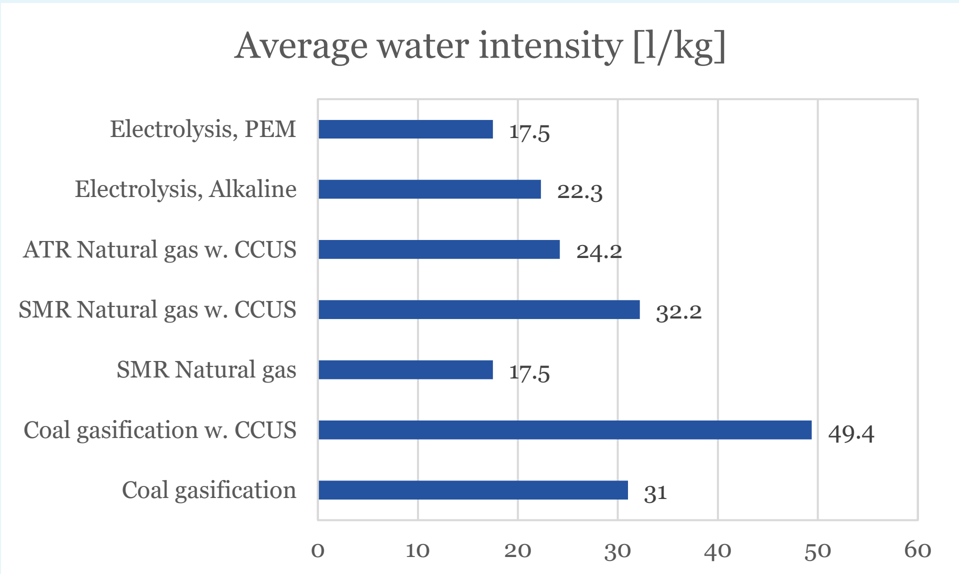

Figure 8. Average water consumption intensities by hydrogen technology [19].

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

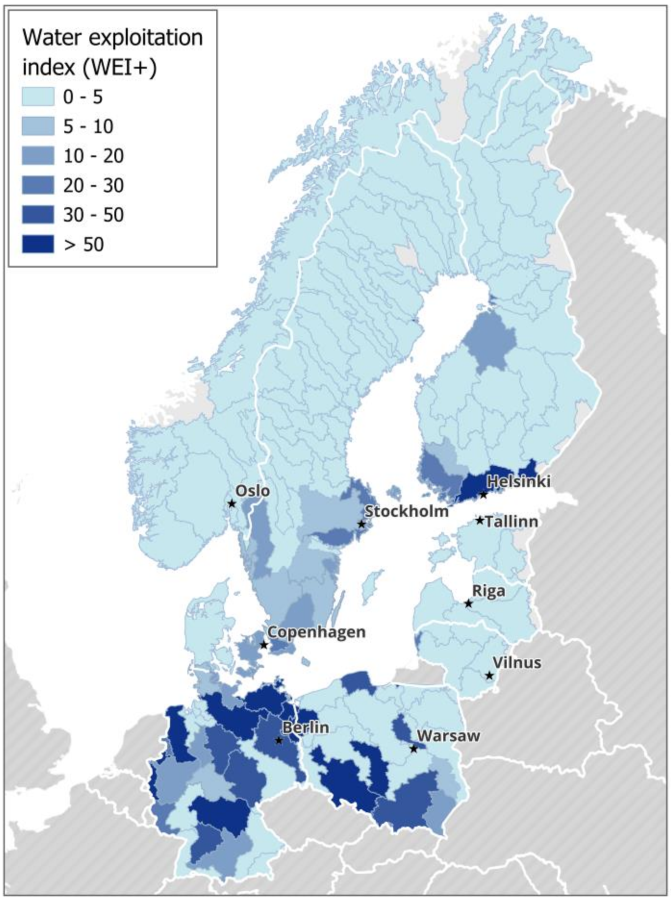

Figure 9. Regional WEI+ values for BSH2 countries in Q3, 2019 [20].

Poland's yearly WEI+ is 8.70%, which is the highest among the countries of Baltic Sea region. However, yearly calculations of the WEI+ at the national level do not account for uneven spatial and seasonal distribution of resources and may therefore hide water stress that occurs on a seasonal or regional basis. For example, southern Poland experiences more water stress compared to north throughout the year.

WEI+
8.70%
BSR range: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (< 0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Poland has remarkable amounts of CO2 available. The annual availability of CO2 is 233 Mt/year (when calculating industrial sources larger than 0,1 Mt/year). The greatest point sources are mainly found close to larger cities (Figure 10). Katowice in Southern Poland is one example of a very high concentration of CO2 sources. There are quite many areas or cities that have substantial amounts of CO2 emissions, and they are mostly located in the Central or Southern parts of Poland. If the CO2 emissions in those areas are of biogenic origin, there could thus be possibilities for power-to-x production plants or CO2 hubs.

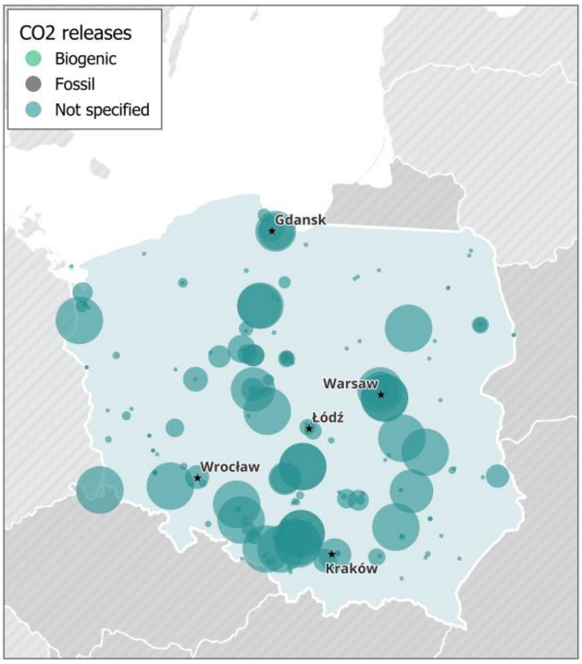

Figure 10. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [21].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

The Polish gas transmission system operator Gaz System operates a natural gas transmission network of above 12 000 km with wide national geographical coverage [22]. For hydrogen transmission, the development centers around a cross-border hydrogen transmission network, that would be established together with Gasgrid, (Finland), Elering (Estonia), Conexus Baltic Grid (Latvia), Amber Grid (Lithuania), and ONTRAS (Germany). The project is called **Nordic-Baltic Hydrogen Corridor** (Figure 11), which has the target to establish a hydrogen transmission infrastructure between Finland, Estonia, Latvia, Lithuania, Poland, and Germany. The cross-border pipeline is scheduled to become operational by 2030 [23].

Figure 11. The Nordic-Baltic Hydrogen Corridor [23].

Despite the plans related to **Nordic-Baltic Hydrogen Corridor,** there are no current national development plans for hydrogen transmission pipelines, and hence the data presented in Figure 12 may be outdated. In Poland, rail and road transport of hydrogen is anticipated to be the main hydrogen transportation method at the beginning of the energy transformation process.

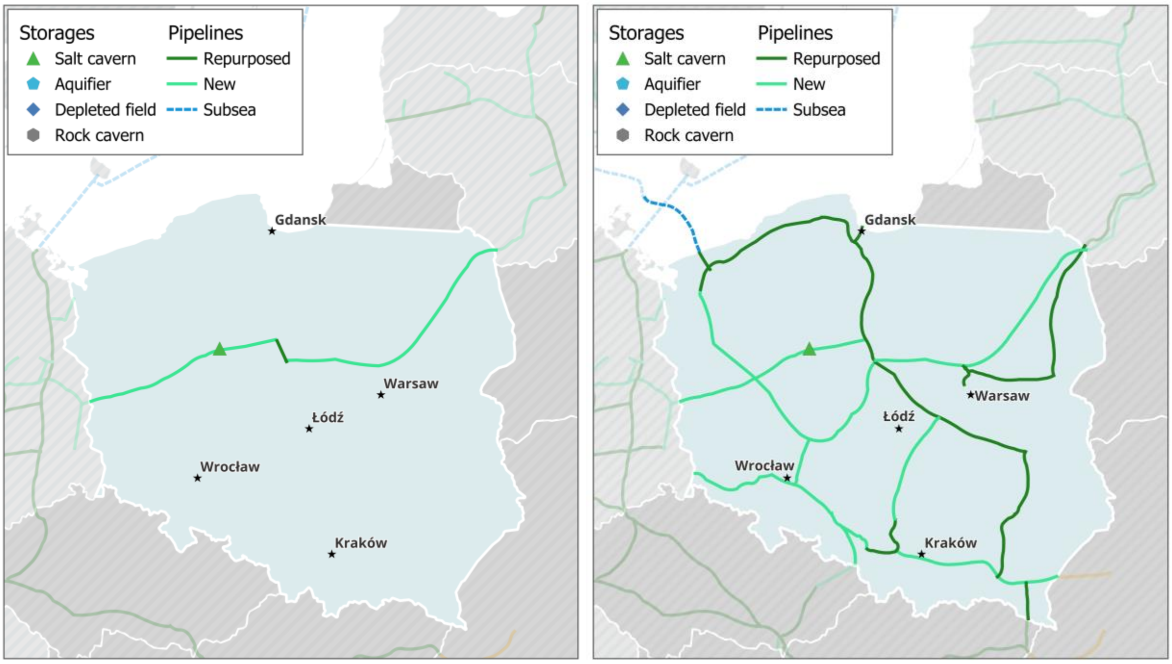

Figure 12. Left: *A European hydrogen infrastructure vision for 2030*. Right: Vision for 2040 *[24]*.

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [25]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which only salt cavern has reached industrial maturity in storing pure hydrogen. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

Currently, Poland has existing salt cavern storages for natural gas with projects underway for additional expansion of underground storage capacity [26]. Geological structures in central-west and north-west Poland give an opportunity for large scale hydrogen storage in salt caverns, which could be used as a buffer storage option for European-wide transport of clean hydrogen and could push for a wider adoption of clean hydrogen in Polish industry. Additionally, Poland's storage capacity could support other European countries, e.g., Baltic states, that don't have suitable geological formations for UHS.

Hydrogen production plans

Significant volumes of fossil hydrogen are already utilized in Poland and the hydrogen used is primarily generated by the end-users themselves. The decarbonization of the industry sector utilizing fossil hydrogen could act as a driving force and create opportunities for hydrogen economy development in

Poland and some companies are already investigating decarbonization alternatives, in which clean hydrogen is also an option.

Based on data collection conducted in BalticSeaH2, the capacity of different projects in the pipeline would result in total estimated electrolytic hydrogen production capacity of above **260 MWe** by 2030**,** once the projects have reached their final phase. It is worth noting that some of the projects in early stages have not disclosed any information regarding their planned production capacities or volumes and are hence excluded from this value.

While not all projects have disclosed their individual capacities, they may have provided estimates of the annual hydrogen production volumes (kt/a). Assuming a 65% electrolyzer efficiency and year-round operational availability for projects that have only provided information of the expected electrolyzer capacity (MW), the planned hydrogen production volume in Poland would be almost **60 kt/a** by 2030. As hydrogen demand in Poland was over 780 kt in 2022 [8], many more projects would have to come online to replace current fossil hydrogen used in the national industry.

In the Figure 13 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project.

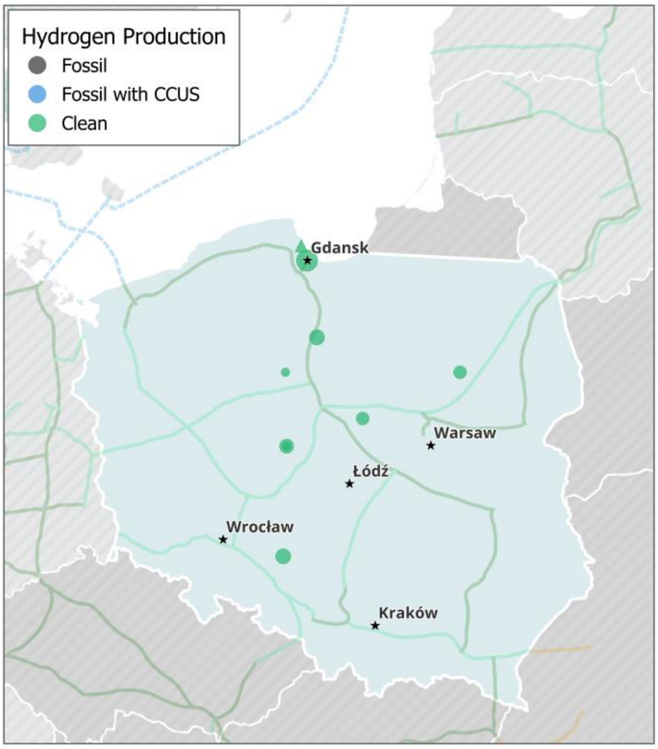

Figure 13. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

Example of an on-going clean hydrogen project in Poland is a project by ZE PAK, in which a 5 MW pilot electrolysis system is constructed to supply 720 tons/a of clean hydrogen for Poland's public bus transport sector with enough hydrogen to fuel above 80 buses. The electrolyzer is powered by electricity generated in on-site solar PV plant (60%) and from external sources (40%). The project has potential scalability to up to 50 MW by 2030, if there is enough hydrogen demand in the transport sector. The project has received innovation fund grant of 4.46 M€ from EU in 2021 [27].

Potential geographical areas for hydrogen development

Several Hydrogen Valley associations and local clusters have been initiated in Poland to foster regional hydrogen development. Each of the Hydrogen Valley associations work with their local hydrogen strategy document mentioning goals and timelines for the implementation of hydrogen technologies. So far only one strategy has been published [28].

The Hydrogen Valley associations with the respective regions and main contributing stakeholders are:

Central Hydrogen Valley "Braci Łaszczyńskich"/Centralna Dolina Wodorowa im. Braci Łaszczyńskich

- **Contributors:** Świętokrzyska Grupa Przemysłowa Industria S.A., ENEA Połaniec, ML System S.A., Łódzka SSE, Energia Europark Mielec, Rolls Royce SMR, Politechnika Świętokrzyska, Instytut Energetyki, regionalne samorządy, ARP S.A., Gaz System, Główny Urząd Miar
- **Plan:** +250 MW electrolyser capacity

Lower Silesian Hydrogen Valley/ Dolnośląska Dolina Wodorowa

- **Contributors:** KGHM Polska Miedź, Grupa Azoty Kędzierzyn-Koźle, ARP S.A., Toyota Motor Manufacturing Poland, Total Energies, Linde Gas Polska, Politechnika Wrocławska, Uniwersytet Wrocławski, Promet-Plast, Polska Spółka Gazownictwa, Gaz-System, Z-Klaster, Dolnośląski Urząd Marszałkowski, Wałbrzyska SSE, Legnicka SSE, Euro-Park Kobierzyce
- **Plan:** + 1700 tonnes of hydrogen annually

Mazovian Hydrogen Valley/ Mazowiecka Dolina Wodorowa,

- **Contributors:** Grupa Orlen, ARP S.A., BGK, Toyota Motor Europe, Instytut Energetyki, Krajowa Agencja Poszanowania Energii, Politechnika Warszawska, Uniwersytet Warszawski, Polska Izba Przemysłu Chemicznego, Siemens Energy, Akademia Górniczo-Hutnicza, Gaz System, Polska Spółka Gazownictwa

West Pomeranian Hydrogen Valley/ Wielkopolska Dolina Wodorowa

- **Contributors:** Zachodniopomorski Uniwersytet Technologiczny, Politechnika Morska, Politechnika Koszalińska, Port Police, Port Szczecin-Świnoujście, Grupa Azoty Police, Enea, ARP S.A.

Greater Poland Hydrogen Valley/ Wielkopolska Dolina Wodorowa

- **Contributors:** Wielkopolski Urząd Marszałkowski, ZE PAK, Solaris, UAM, Politechnika Poznańska, Miasto Śrem, Miasto Piła, Lotnisko Poznań – Ławica,
- Plan: 10MW electrolysis capacity

Silesia-Lesser Poland Hydrogen Valley/ Śląsko-Małopolska Dolina Wodorowa

- **Contributors:** Politechnika Rzeszowska, Polenergia Nowa Sarzyna, Autosan, ML System, Podkarpacki Urząd Marszałkowski, ARP o/Tarnobrzeg, Instytut Energetyki
- Plan: 5 MW electrolysis capacity

Pomeranian Hydrogen Valley/Pomorska Dolina Wodorowa

- **Contributors:** Pomorski Urząd Marszałkowski, Sescom, Politechnika Gdańska, Nexus, Klaster Technologii Wodorowych, Grupa ASE

Lublin Hydrogen Cluster/Lubelski Klaster Wodorowy

- **Contributors:** Grupa Azoty Puławy, Lubelski Węgiel Bogdanka, Lubelski Park Naukowo-Technologiczny, Lubelski Urząd Marszałkowski, Sieć Badawcza Łukasiewicz

Education and employment

All leading technical universities in Poland have already integrated hydrogen-related topics into their curricula, either as dedicated fields of study or within relevant disciplines. The foremost technical universities include those in Warsaw, Gdańsk, Lublin, Poznań, Wrocław, and AGH Kraków.

Regarding upskilling and reskilling of the existing workforce, there are numerous post-graduate programs available at both public universities, which are prominent in scientific research, and private universities, which operate as profitable entities. However, these programs primarily focus on management, such as MBA courses with an emphasis on hydrogen technologies and the market.

From the perspective of regional employment, hydrogen activities have the potential to address social and unemployment issues in every region. In Poland, highly industrialized areas such as Silesia, Lower Silesia, Lesser Poland, Greater Poland, Mazovia, and Pomerania host heavy and energy-intensive industries that require decarbonization. As a result, technical staff in these regions will need to undergo retraining, such as relevant post-graduate studies, or adapt to the evolving job market skills. While this transition poses risks for current job holders, it also presents opportunities for both employed and unemployed individuals. Additionally, regional migration is anticipated.

In less industrially developed regions where agriculture is predominant, such as those with potential for renewable energy sources like PV and wind farms, hydrogen activities could drive sustainable development. Given that large energy consumers are typically located far from these areas, local production of hydrogen might be a key for sustainable development of regions. This shift will necessitate new types of workers, meaning that any initiatives related to renewables and hydrogen will have significant social impacts on these regions.

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [29]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [30]. Recent survey [31] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [32]. The rise of right-wing politics and growing “greenlash” against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [33].

Another barrier potential barrier stems from a community-rejection (also referred to as, the NIMBY-effect, “Not In My Backyard”), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [31], [34], [35], [36], [37]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [38].

The success of this community ownership model in driving Denmark’s wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [31], [32] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

In the Polish context, there remains little research on the socio-political and community acceptance of hydrogen technologies. However, recent opinion polls suggest relatively high hydrogen awareness in Poland, and high public sentiments towards wind power and nuclear energy [29], [30]. In comparison to other Baltic Sea states, the Polish public is among the most concerned about reducing energy dependency on Russia [30]. Furthermore, public acceptance of nuclear power is also among the highest in the Baltic Sea region, which could open routes to pink hydrogen as well.

Whilst local opposition to wind power is not as prominent in Poland as it is in other Baltic Sea region states (such as Norway, Sweden, and Finland), a recent government decision [39] to reduce the minimum distance between wind farms and housing may lead to an increase in local opposition.

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Appendix I

Country profile Germany

Contents

Summary of national opportunities and challenges

Opportunities	Challenges
Robust industrial base with multiple companies involved in hydrogen production and infrastructure development	Limited availability of qualified hydrogen experts
Established infrastructure and expertise in gas processing	Supply chain limitations, especially electrolyzers
Demand for clean hydrogen from heavy industry to meet decarbonization targets	Insufficient clean electricity production capacity
Strong governmental promotion with funding schemes and quantified targets in the national hydrogen strategy	Limited public knowledge on hydrogen and hydrogen technologies
Quantified targets and support schemes for wind and PV capacity building	
Significant potential for large-scale hydrogen storage	
International collaborator – drives the hydrogen economy development in other countries	
Multiple degree programs on hydrogen technology and large offering on reskilling and upskilling training	

National hydrogen strategies and targets

The **National Hydrogen Strategy** [1] of Germany was published by Federal Ministry for Economic Affairs and Energy in 2020. The strategy was updated in 2023 [2]. The update of the National Hydrogen Strategy (NWS) in Germany includes various measures to promote the production, transportation and use of hydrogen and its derivatives. The Federal Government forecasts of 95-130 TWh of hydrogen demand in Germany by 2030. The strategy acknowledges that the required quantities of hydrogen for the energy transition in Germany cannot be solely produced within the country due to limitations in the renewable energy capacity. Hence, around 50-70% of the hydrogen demand is expected to be covered from imports of hydrogen and its derivates.

The National Hydrogen Strategy includes expanding the production of hydrogen and hydrogen derivatives in Germany, importing hydrogen and hydrogen derivatives, building an efficient hydrogen infrastructure, and strengthening research, innovation and the training of skilled workers. The production of hydrogen is energy-intensive, which is why it should primarily be used where the direct use of renewable electricity is not possible or not economical. The German government plans to provide several billion euros from federal and state funds to promote the production, development of infrastructure and use of hydrogen. The NWS is intended to help Germany maintain and further expand its strong position in hydrogen technologies. The update of the NWS also sets state guidelines for private investment in sustainable, particularly economic, ecological and social hydrogen projects. The German government has set itself the goal of achieving a reliable supply of green, long-term sustainable hydrogen in Germany and committing to ambitious sustainability standards for hydrogen and its derivatives.

Hydrogen Strategy/Roadmap
Yes
National Hydrogen Strategy (2020, updated in 2023)

The strategy outlines various targets to achieve by 2030, which can be summarized as follows:

- Increase electrolysis capacity for hydrogen production to at least **10 GW by 2030** to ensure sufficient availability of hydrogen and its derivates, with the remaining demand covered by imports
- Development of a hydrogen grid, including both repurposed and newly built pipelines, with a length of more than **1,800 kilometers by 2027/2028** with the help of IPCEI funding
- Implementation of hydrogen applications in different sectors by 2030, in particular in industry and heavy-duty vehicles, and increasingly in aviation and shipping
- As a goal, Germany companies will have leading role in providing hydrogen technologies by 2030 covering the entire process chain from production (e.g. electrolysers) to the various applications (e.g. fuel cell technology)
- Creating appropriate framework conditions to speed up hydrogen market ramp-up on national, European and even international level, with specific focus on efficient planning and approval procedures, uniform standards and certification systems and coordinated administration

Quantified targets for hydrogen production
Yes
•10 GW electrolyzer capacity (2030)

National networks

Intensive collaboration among stakeholders is underway to advance hydrogen initiatives in Germany. This collaboration involves diverse clusters, joint ventures, and partnerships across various sectors and regions.

Examples of the networks under the Federal Ministry of Digital and Transport (BMDV) Cluster:

- **Clean Power Net** is a nationwide consortium of companies across the value chain, aiming to provide industrial users with a more efficient and climate-friendly energy supply. Its focus is on fuel cell applications for industry and business, offering technical advantages such as high reliability, longer bridging times, lower energy consumption, off-grid capabilities, and zero local emissions. [3]
- **Clean Intralogistics Net (CIN)** focuses on fuel cells in intralogistics [4] https://www.cleanintralogistics.net/en/
- **e4ships** focuses on fuel cells in maritime applications [5] https://www.e4ships.de/english/about/
- **Clean Port & Logistics (CPL)** is a cluster for testing hydrogen-powered equipment in port logistics [6] https://hhla.de/en/innovation/hydrogen-at-hhla/clean-port-logistics
- **Brennstoffzellenbus-Cluster**/Fuel cell bus cluster [7]

Examples of the networks under the Federal Ministry of Economic Affairs and Climate Action (BMWK) Cluster:

- **The German National Hydrogen Council** (NWR), appointed by the German government, serves as an independent, non-partisan advisory board. Comprising 26 esteemed experts from the realms of economy, science, and civil society, its mission is to support and advise the State Secretaries' Committee on Hydrogen in advancing and executing Germany's National Hydrogen Strategy (NWS). [8]
- **Trans4Real** focuses on transferring knowledge from living labs for the energy transition, particularly regarding hydrogen's role in achieving a climate-neutral Germany. Supported by the BMWK's Energy Transition living labs funding, the project disseminates insights from living labs to foster collaboration between science, politics, and industry. Structured into three levels, Trans4Real aims to scale up knowledge through the accompaniment, reflection, and synthesis levels. Led by the FfE, the project encompasses tasks like accompanying living labs, life cycle assessments, energy system integration, market analysis, and deriving action approaches. The consortium includes Dechema, Zentrum für BrennstoffzellenTechnik GmbH, Agora Energiewende, Stiftung Umweltenergierecht, Ruhr Universität Bochum, and TU München – Hochschule für Politik [9]
- **Hydrogen Research Network** [10]

Additionally, there are regional collaborations in Mecklenburg-Vorpommern, Saxony, Berlin, Brandenburg, Saxony-Anhalt

Hydrogen state-of-play

In Germany, a significant volume of hydrogen is already produced and utilized as a feedstock for ammonia and methanol production and within the refining sector (Figure 1). In addition, there are also several other uses for hydrogen as well, including mobility, industrial and residential heat, e-fuels, steel industry and power generation.

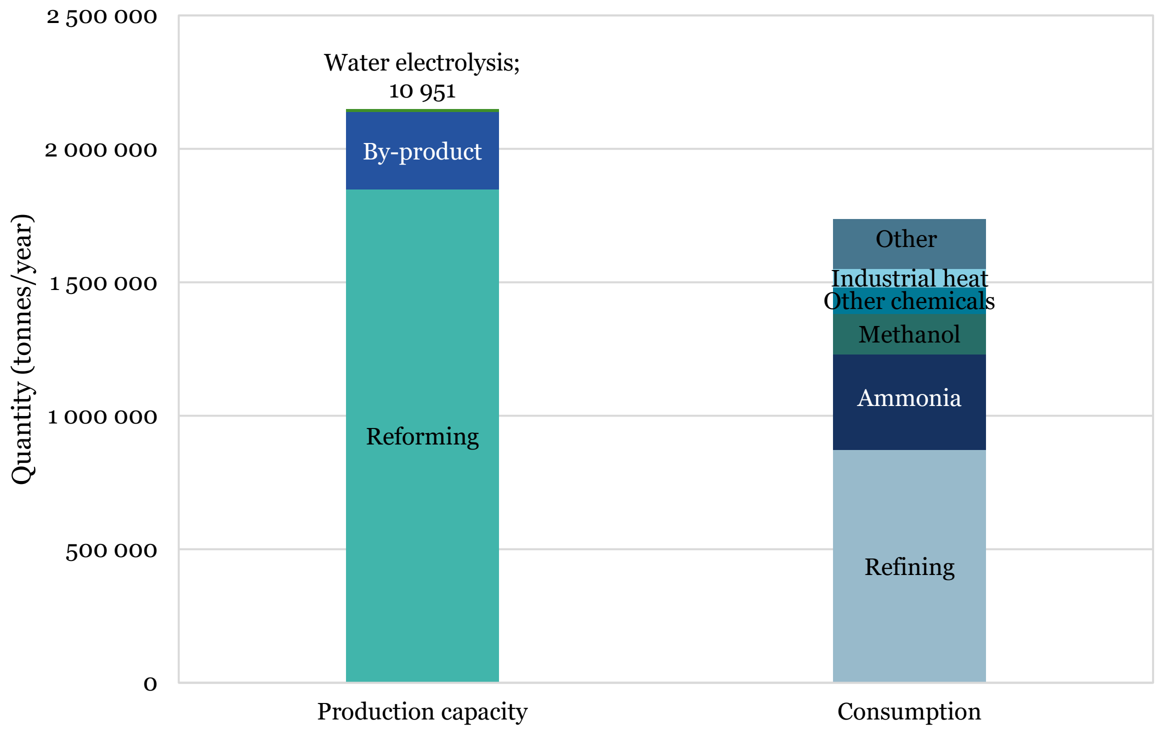

Figure 1. Hydrogen production and consumption in Germany [11].

The annual dedicated hydrogen production in Germany is approximately **1 860 kt/a**. Assuming that 1 848 kt/a s produced via by steam methane reforming (SMR) with carbon intensity of 9 kgCO2/kgH2, decarbonising Germany's fossil-based hydrogen production would lead to 16 630 kton of CO2 reduction, which corresponds **2.2 %** of Germany's total CO2 emissions (total emissions 2021: **760 358** kton CO2-eq excl. LULUCF [12]). The location of the operational hydrogen production facilities is presented in below in Figure 2.

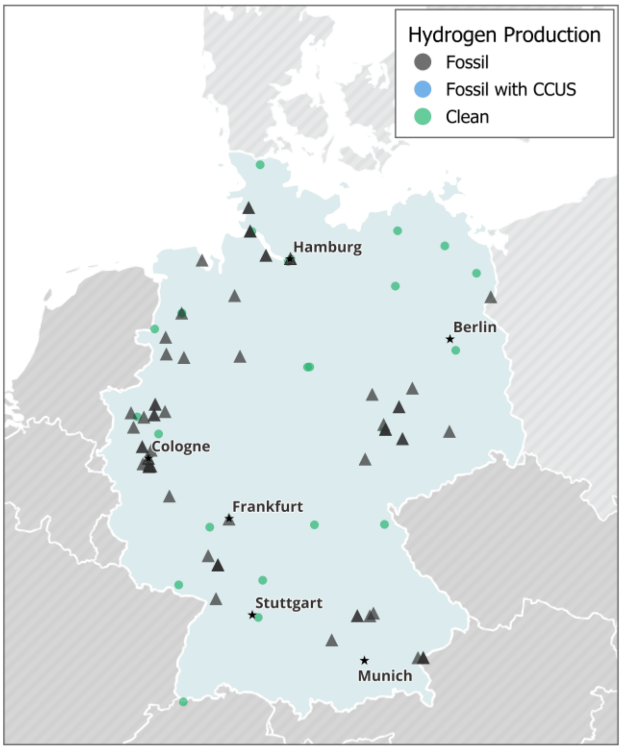

Figure 2. Operational hydrogen production facilities. Facilities with unspecified capacity indicated by triangle markers [13].

Existing hydrogen consumption sources	CO_2 reduction potential in current fossil hydrogen production
1 740 kt/a	**2.2%**
Baltic Sea region: 0–1 750 kt/a	Baltic Sea region: 0–11.9% of total CO_2 emissions

Hydrogen opportunities

Industry

Use of clean hydrogen is anticipated to start from sectors where fossil hydrogen is already used today and in applications where no other feasible alternatives for decarbonisation exist. These applications include, for example, ammonia and methanol production, as well as hydrogen use in refineries. The largest consumer of dedicated hydrogen globally is ammonia production, where hydrogen is synthetized with nitrogen to create ammonia, which in turn is mostly used in fertilizer production. Methanol is a base chemical for a wide range of products, such as plastics, paints, and fuels. In oil refining, hydrogen is used, for instance, to improve and upgrade the quality of crude oil through hydrogenation process. Approximately 80% of the hydrogen used in global refinery operations was produced onsite in year 2022, of which around 55% was dedicated hydrogen production [14]. The remaining fraction of the hydrogen is produced as a by-product from different refinery operations.

In the beforementioned sectors, a like-for-like substitution of fossil hydrogen by clean hydrogen is possible, excluding by-product hydrogen use in refining. Hydrogen molecules produced using renewable energy are indistinguishable from fossil-derived hydrogen, thus the amount of hydrogen used per unit of produced ammonia, methanol or refined oil remains unaffected by whether the hydrogen is generated through electrolysis or is of fossil origin.

As for the new industrial applications for clean hydrogen, considerable emission reductions can be achieved especially in the steel industry, which produces around 7% of global and 5% of EU's CO_2 emissions. In EU, the main decarbonisation pathway for steel industry seems to be the hydrogen-based steel making via direct reduction of iron ore (DRI), which can replace the highly CO_2-intensive blast furnace-based steel production. Unlike the like-for-like substitution of fossil hydrogen to clean hydrogen in ammonia and methanol production and in oil refining, the decarbonisation of steel industry via hydrogen will require significant changes in the entire production process of primary steel [15].

Germany is a very industry-intensive country and the demand for clean hydrogen from heavy industry to meet decarbonization targets is an important driver for clean hydrogen uptake in the country. Significant decarbonization potential exists in sectors such as refining and ammonia production, which are the primary industries utilizing hydrogen in Germany today. One ammonia production facility and six refineries are located in the North-East Germany and the regions closest to the Baltic Sea. The estimated annual hydrogen consumption volume of the ammonia production facility is 45 kt, and the capacities of the oil refineries are 11.8 Mt, 11.3 Mt, 5.2 Mt, 4.5 Mt, 3.1 Mt and 0.8 Mt of crude oil annually [16]. In these plants, fossil hydrogen could be replaced with a clean alternative through a like-for-like substitution.

Primary steel production is another important sector for Germany, where clean hydrogen could significantly contribute to decarbonization efforts. In the analysed region, there are three primary steel production sites with annual steel production capacities of 2 400, 3 800 and 5 200 kt/a [17]. As an example of on-going decarbonization efforts in the steel industry, ArcelorMittal plans to gradually replace its blast furnaces in Eisenhüttenstadt and Bremen with a hydrogen-based DRI process [18]. Initially, hydrogen will be produced from natural gas until it becomes available from a dedicated hydrogen pipeline.

Locations of the beforementioned example industrial plants in North-East Germany with potential for clean hydrogen use in decarbonisation are mapped in Figure 3.

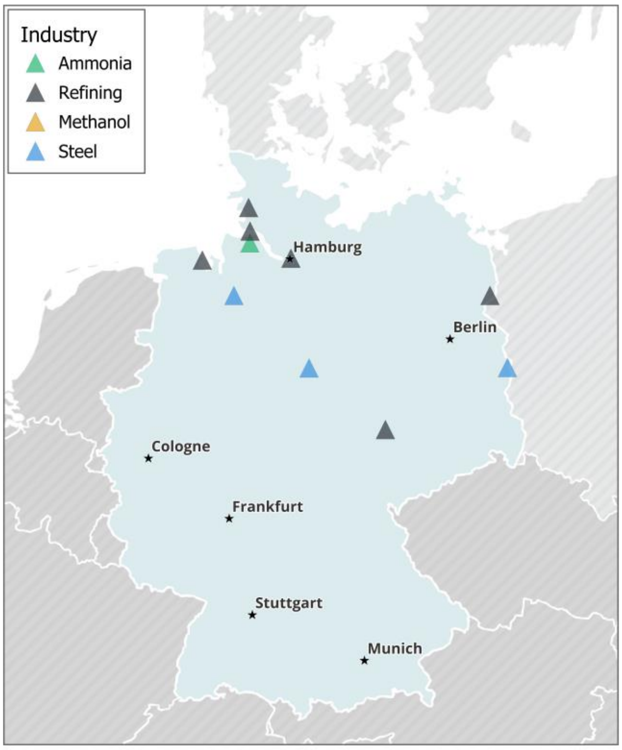

Figure 3. Locations of example industrial plants in North-East Germany and the regions closest to the Baltic Sea with potential for clean hydrogen use in decarbonisation.

Ammonia production	Refineries	Steel production
45 kt/a (hydrogen)	**37 Mt/a (crude oil)**	**11 400 kt/a (steel)**
Baltic Sea region: 45–374 kt/a (hydrogen demand)	Baltic Sea region: 9–37 Mt/a (crude oil)	Baltic Sea region: 2 600–11 400 kt/a (steel)

NB! Covers facilities located in North-East Germany and the regions closest to the Baltic Sea.

Transport and logistics

Hydrogen can be used in mobility applications directly as pure hydrogen, or indirectly, converted to other hydrogen-containing compounds. Generally, direct electrification is more desirable to replace fossil fuels in mobility due to a better round-trip efficiency of electric battery. However, certain boundary conditions can justify the use of hydrogen-powered vehicles. These conditions include, for example, the need for extended operating range, short refueling time and subsequent operational flexibility, or minimizing the weight of the vehicle. Hydrogen-based technologies are more favourable compared to direct electrification for hard-to-abate sectors such as heavy-duty transport where direct electrification is hard to achieve. This is true especially with long-haul heavy-duty transport because of the long transport distances.

Vehicles that are under intensive use in city logistics (e.g., buses, taxis, waste trucks) but also in regional and long-haul operations (e.g., trucks, lorries) as well as maritime applications are potential users for hydrogen. In addition, non-road mobile machinery (e.g. forklifts, cranes, loaders) used in

agriculture, construction sites, mining, material handling and forestry have potential to decarbonize using clean hydrogen instead of direct electrification.

The transportation sector, including public and freight road transport, maritime, and aviation, accounted for 161 million tons of CO2-equivalents (21.5% of total emissions in Germany), with the need for new infrastructure and further research in some areas. Road transport sector accounts for approximately 96% of transport-related emissions in Germany, with 61% of these emissions attributed to passenger cars. While there is significant potential for emission reduction in passenger car traffic, the use of hydrogen is considered advantageous only in a few cases.

Germany is making notable progress in hydrogen vehicle technology, aiming to be a global pioneer in hydrogen vehicle markets. With the third-largest hydrogen vehicle fleet globally, over 1000 passenger vehicles are on the roads. Cities like Köln, Wuppertal, and Frankfurt lead in public transport's hydrogen adoption, with 145 buses in operation [19]. Public transport operator Ruhrbahn plans to replace its diesel buses with hydrogen ones by 2033 [20]. The current hydrogen demand in the transportation sector is approximately 45 tons per year.

The federal government commits to investing in hydrogen vehicles and making public buses and trains more attractive. The previous support programs included, for example, National Innovation Program Hydrogen and Fuel Cell Technology (NIP) Phase II 2016 – 2026 and Promotion of alternative drives for buses in passenger transport, funded by the Federal Ministry of Digital and Transport (BMDV). However, BMDV announced in February 2024 that the funding programs for climate-friendly commercial vehicles and for alternative drive systems for passenger buses will be discontinued [21].

Germany has also experimented with hydrogen on railways, when the first train powered by fuel-cell ran in Lower Saxony region for one year. The fuel-cell train system was closed because of high operating cost and the region opted to continue the replacement of diesel trains with battery-electric trains [22]. This example, even though it did not prove to be cost-effective, demonstrates the dedication to exploring various decarbonization options and trying to identify the best applications for hydrogen.

Shipping and ports are another well-advancing part of Germany’s hydrogen economy building, with large-scale hydrogen investments being built in harbour areas. For example, Port of Hamburg is building an ammonia import terminal, which will be equipped with ammonia cracking facility to break down ammonia into hydrogen and nitrogen [23]. This allows the imports of hydrogen in form of ammonia, which is very hydrogen-rich compound, starting from 2026. Additionally, a 10 MW hydrogen production facility in Brake harbour area broke ground in February 2024 [24].

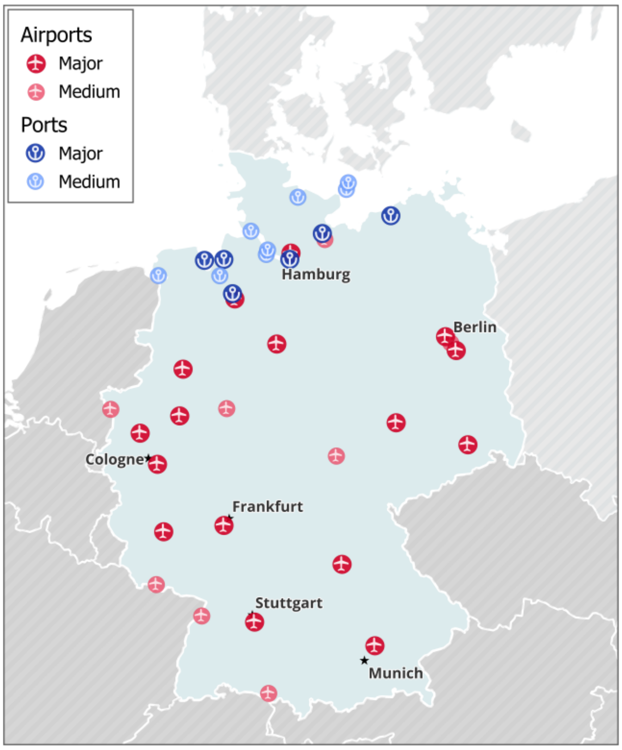

Figure 4. Key ports and airports: ranked by cargo weight (> 3 Mt/year) and passenger traffic (> 1.5 million) [25].

Share of fossil fuels in energy use of road transportation	Share of fossil fuels in rail transport	Energy demand of domestic navigation
94%	**20% (252 ktoe)**	**236 ktoe**
Baltic Sea region: 71–98%	Baltic Sea region: 5–92%	Baltic Sea region: 1–1280 ktoe

Based on [25]

Hydrogen refueling infrastructure

The majority of hydrogen refueling stations in Europe are situated in Germany, where nearly 100 operational stations currently exist [26] (Figure 5). Therefore, the hydrogen refueling infrastructure in Germany is the most advanced among the European countries and a significant number of hydrogen refueling stations are being planned to further expand the network.

H2Mobility is the main builder of the current refueling infrastructure in Germany [27]. H2Mobility was established in 2015 through a collaboration among six industrial companies: Air Liquide, Daimler, OMV, Linde, Shell, and TotalEnergies. By 2022, the project evolved into a commercially focused company, with the Clean H2 Infra Fund managed by Hy24 emerging as the primary investor. Additional investments were made by Shell, Air Liquide, TotalEnergies, Linde, Daimler Truck, EG Group, and Hyunda.

The hydrogen refueling network of H2Mobility supplies hydrogen at 700 bar to passenger cars and light commercial vehicles in seven German metropolitan regions (Hamburg, Berlin, Rhine-Ruhr, Frankfurt, Nuremberg, Stuttgart and Munich) and on the connecting roads and highways [27]. In key locations, the company is expanding the 700-bar hydrogen infrastructure to also include 350-bar refueling interfaces. This enhancement enables heavy-duty vehicles like trucks and buses to also refill hydrogen. H2Mobility reports that Germany's nearly 100 hydrogen refueling stations make hydrogen mobility accessible to over 6 million people within a 5-kilometer radius.

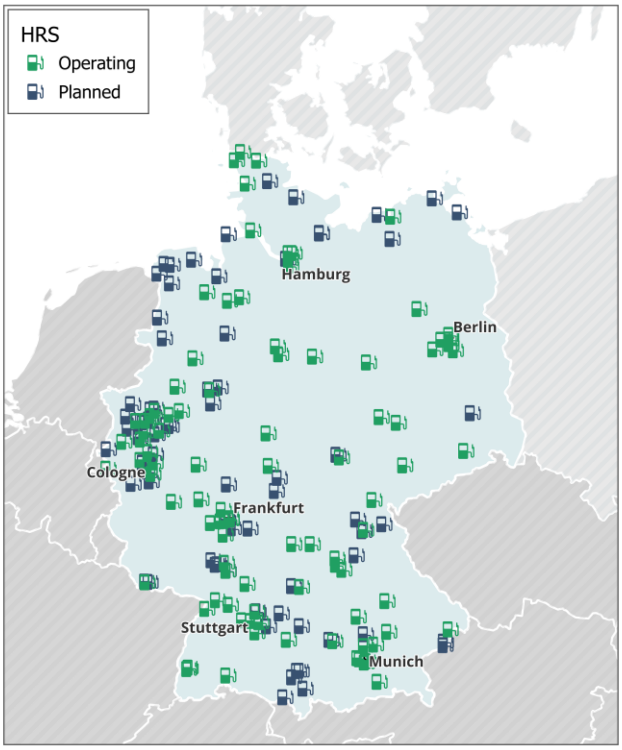

Figure 5. Operating and planned hydrogen refueling stations [26], [28] and publicly announced projects.

Resource availability

Renewable electricity production

Germany has ambitious targets for the expansion of renewable electricity. The aims are to reach a minimum of 30 gigawatts (GW) of offshore wind power capacity by 2030 (1 GW current capacity), 40 GW by 2035, and 70 GW by 2045, while doubling onshore wind capacity to 115 GW by 2030. This growth will help to transition away from coal and reduce the reliance on natural gas, but Germany will remain a net importer of energy and hydrogen. The recent trends in renewable electricity generation capacity in Germany are illustrated in Figure 6.

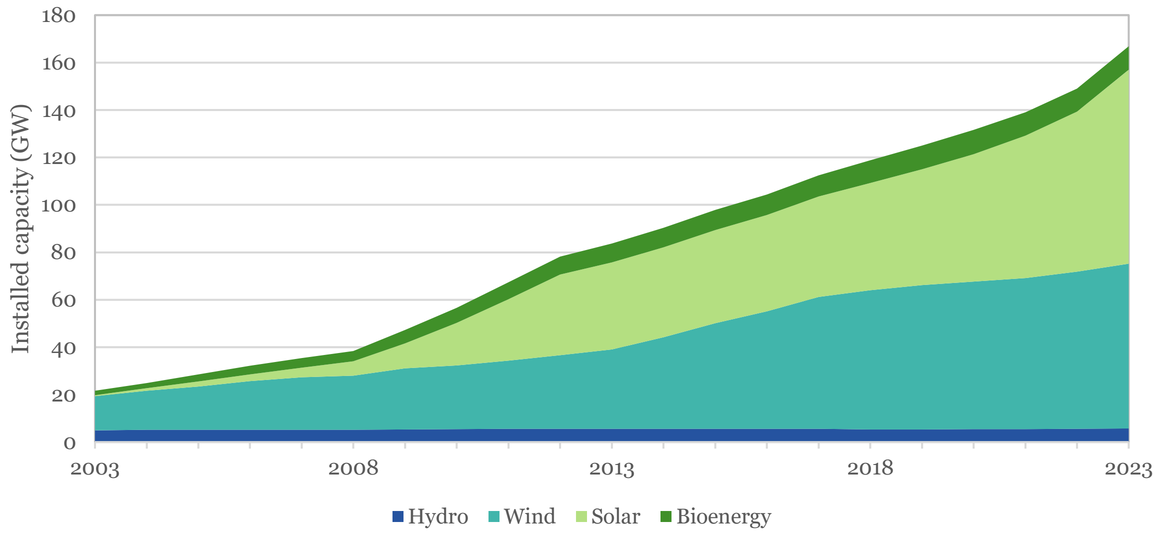

Figure 6. Renewable electricity generation capacity in Germany between 2003-2022 [29].

Within BalticSeaH2 project, data from publicly available sources has been collected to identify the renewable electricity projects with a capacity greater than 10 MW and that are not yet operational. As for Germany, the data was collected for the region covered by the federal states of Mecklenburg-Vorpommern, Brandenburg, Berlin, Sachsen-Anhalt and Sachsen (North-East Germany). These projects include 1.1 GW solar energy, 2.2 GW of onshore wind energy, and 2.1 GW of offshore wind energy, totaling **5.5 GW** of new renewable electricity capacity in the pipeline (Figure 7).

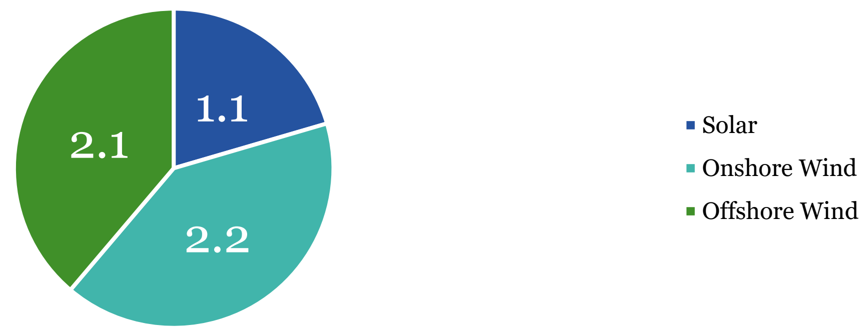

Figure 7. Renewable electricity projects (GW) in pipeline in North East Germany based on data collection conducted in BalticSeaH2.

The German government has agreed a power plant strategy that provides for the construction of new hydrogen-capable gas-fired power plants to replace coal and nuclear power plants that have or will be decommissioned in the coming year. These are to be gradually converted from natural gas to clean hydrogen from 2035 to 2040 to ensure a climate-friendly energy supply. The new gas-fired power plants are to serve as a reserve for times of low solar and wind energy and thus ensure security of supply. The switch to clean hydrogen is to be scheduled for 2032. The strategy also envisages the construction of pure hydrogen power plants, with up to 25 gigawatts of new capacity forecast, which corresponds to around 50 new power plants. The power plants will be highly subsidized by the government. Hydrogen shall therefore be a central element in the integration into Germany's energy landscape [30].

Water

Water is needed in all hydrogen production technologies for production and cooling. Assessing the potential implications on hydrogen and water usage, especially in already water-stressed areas is important as hydrogen production can be disrupted due to water shortage. The impact of hydrogen production's water usage depends on the location and used technology. Figure 8 presents the average water intensity of hydrogen production technologies. As natural gas SMR is the most frugal technology in terms of water usage, paralleled by PEM electrolysis, the water usage of hydrogen production will grow as the production becomes cleaner in terms of CO2 emissions if the production rate remains constant or increases.

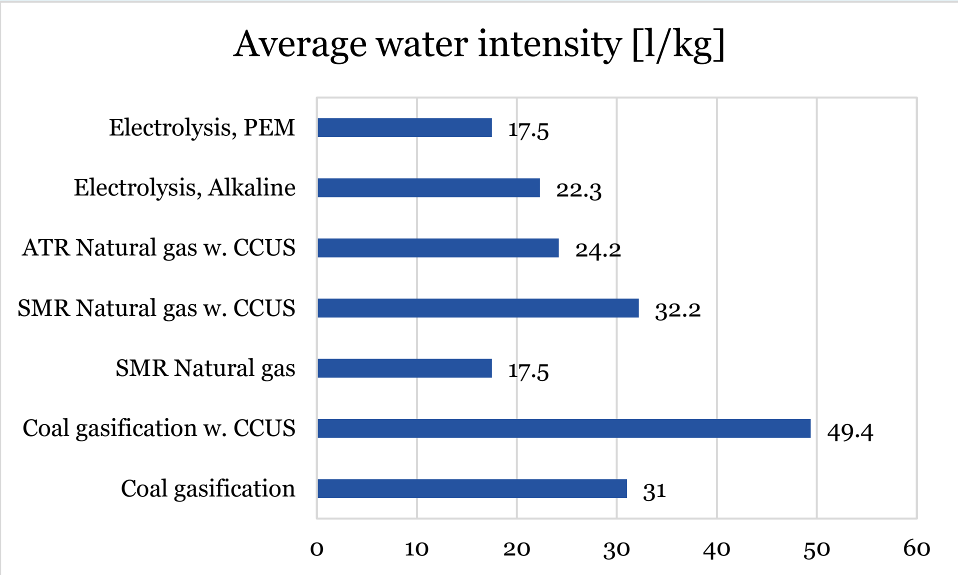

Figure 8. Average water consumption intensities by hydrogen technology [31]

Water usage intensity can be described using The Water Exploitation Index Plus (WEI+), which is a metric used to assess water stress by considering the ratio of water use to renewable freshwater resources. WEI+ values exceeding 20% signal the presence of stress on water resources, indicating prevailing water scarcity conditions.

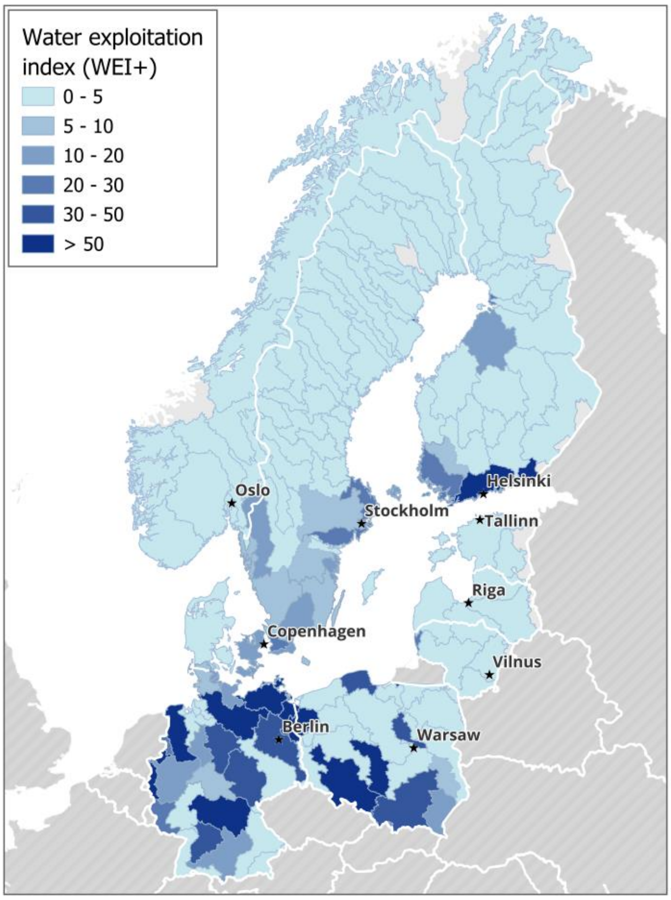

Figure 9. Regional WEI+ values for BSH2 countries in Q3, 2019 [32].

The local water stress conditions determine that 33% of the hydrogen projects that are operating or planned in Germany are in areas with low water stress, 18% are in areas with low to medium water stress, 32% in areas with medium to high water stress, and 16% are in areas with high water stress risk [31]. As the number of water electrolysis projects in Germany is high, the expected hydrogen projects involving water electrolysis would raise hydrogen production in Germany by tens of millions of cubic meters. In general, Germany does not face water scarcity and its yearly WEI+ is 2.57%. However, yearly calculations of the WEI+ at the national level do not account for uneven spatial and seasonal distribution of resources and may therefore hide water stress that occurs on a seasonal or regional basis – the seasonal water scarcity conditions varied considerably in Germany in 2019, where northern and central parts of Germany were the most water stressed.

WEI+
2.57%
Baltic Sea region: 0.07–8.70%

Availability of CO_2

Further processing of hydrogen to other products, such as hydrocarbons, often needs CO2. Many countries see the production of e-fuels, chemicals, or other types of products as an attractive option for hydrogen use, especially as an option to additional value. In the effort to move away from fossil production, biogenic sources are seen as a more sustainable choice for CO2 feedstock. Biogenic CO2 can be captured from various sources, such as recovery boilers of a pulp mill or from exhaust streams of biorefineries.

Therefore, the availability and types (fossil, biogenic) of CO2 sources in the region are important for hydrogen opportunities. The CO2 sources are different to each other, e.g., some have greater amounts in one place, as point sources, which allows capturing large amounts of bio-CO_2 from a single location, possibly reducing the need for transport. Other sources might have a higher CO2-concentration in the stream, allowing a lower cost and less effort in the CO2 capture. The sources of CO2, or possible CO2 hubs, could offer synergies for hydrogen and converting it to other products.

The availability figures for CO2 for all countries are from The European Pollutant Release and Transfer Register (E-PRTR). For each facility in E-PRTR, the newest emission value reported after 2017 is used. E-PRTR includes CO2 emissions higher than 0.1 Mt/year from industrial facilities and large combustion plants. This value differs from the country's total annual CO2 emissions. Annual CO2 emissions including smaller plants (< 0.1 Mt/year) and other sectors (e.g. traffic) should be found elsewhere if needed.

Germany has substantial amounts of CO2 available. The annual availability of CO2 is 379 Mt/year (when calculating industrial sources larger than 0,1 Mt/year). The locations are mainly found close to larger cities, for example Cologne in Western Germany has the largest concentration of CO2 sources (Figure 10). Also, synergies could be found between Frankfurt and Stuttgart in the Southwest. The Eastern part of Germany has significant amount of CO2 in one area, mainly around cities such as Dresden, Leipzig, Cottbus, and Berlin. If the CO2 emissions in some of these sources are of biogenic origin, there could thus be possibilities for CO2 hubs or power-to-x production plants.

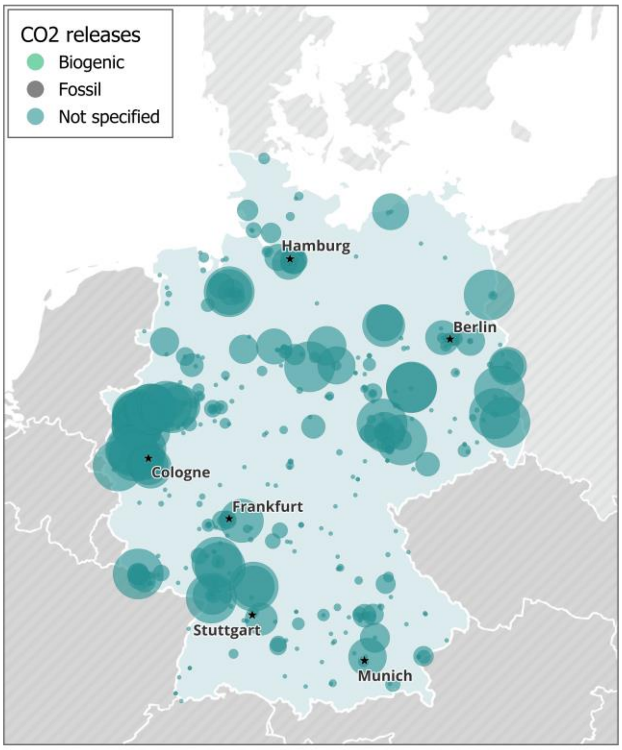

Figure 10. CO2 emissions from industrial facilities and large combustion plants exceeding 0.1 MtCO2/year [33].

Infrastructure availability

Hydrogen pipeline transmission infrastructure

Germany's natural gas infrastructure is managed by three operators: OGE, ONTRAS Gastransport GmbH, and GASCADE Gastransport GmbH, with networks spanning 12 000 km, 7 700 km, and 3 200 km, respectively. All these operators are actively involved in the development of Germany's hydrogen transmission infrastructure and the core hydrogen network. The draft proposal for the core hydrogen network was submitted for review to the Federal Network Agency and the Federal Ministry of Economics and Climate Protection in November 2023 [34], [35].

The core hydrogen network, spanning a total length of 9,700 km, primarily utilizes repurposed natural gas pipelines, accounting for approximately 60% of its length. The estimated investment cost for the network amounts to €19.8 billion, with plans to be completed in phases between 2025 and 2032. The objective is to interconnect Germany's core hydrogen network with various regions, including the Netherlands, the North Sea, Denmark, Poland, and the Baltic Sea to the north; Austria and the Czech Republic to the southeast; Belgium and France to the west; and Poland to the east [35].

One example of such interconnection is the **Nordic-Baltic Hydrogen Corridor** project, which plans to establish a hydrogen transmission infrastructure between Finland, Estonia, Latvia, Lithuania, Poland and Germany [36]. In addition, **Baltic Sea Hydrogen Collector** project evaluates the opportunity to build a subsea hydrogen transmission pipeline infrastructure connecting Finland, Sweden, and Germany [37]. Both of the cross-border pipelines are scheduled to become operational by 2030.

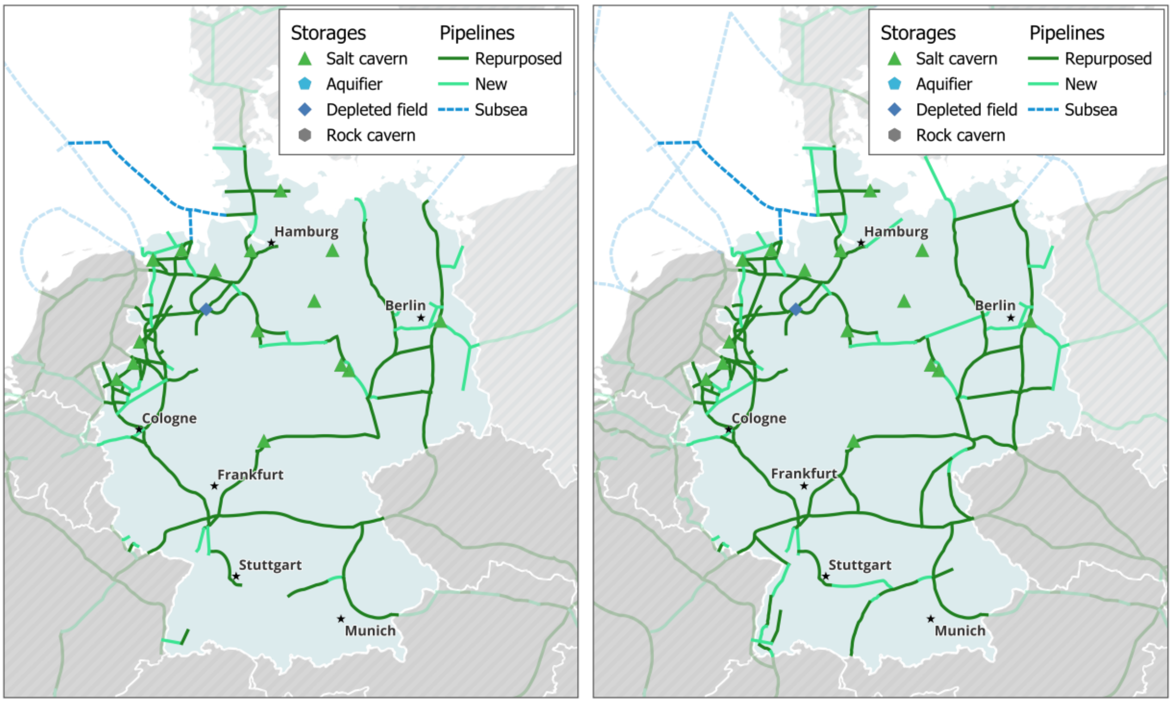

Figure 11. Left: A European hydrogen infrastructure vision for 2030. Right: Vision for 2040 [38]

Hydrogen storage

Compared to other gases, such as methane, hydrogen storage is more challenging due its low volumetric density. Thus, hydrogen is typically produced on-site with limited storage capacity. However, with the increase on clean hydrogen production and use, as well as the need to couple variable renewable electricity production with energy storage, considerably more hydrogen storage capacity will be needed. In January 2024, the plans for pure hydrogen storage capacity by 2030 totaled 9.1 TWh, while the estimated optimal hydrogen storage capacity in Europe in 2030 is 40 – 50 TWh and continues to grow beyond 2030 [39]. This necessitates a massive rollout of underground hydrogen storage (UHS) capacity in the coming years. Currently, the underground gas storing take place in salt caverns, depleted gas fields, aquifers, and rock caverns, of which only salt cavern has reached industrial maturity in storing pure hydrogen. UHS technologies have the means to provide flexibility over various timescales, from days to years, depending on the technology. Currently, no UHS capacity storing pure hydrogen is present in BSH2 countries apart from a test facility in Sweden.

Germany has little gas reserves of its own, but it has about a quarter of the EU's gas storage capacity. In 2021, Germany had 255 TWh working gas capacity, mostly in salt caverns in north-west Germany [40]. Germany is well-positioned for UHS as it can use its existing salt cavern capacity for hydrogen, and play a central role in the European hydrogen market. Germany also has the most advanced plans among BSH2 countries for large-scale hydrogen storage. For instance, German energy company Uniper plans to build 260 – 600 GWh of salt cavern hydrogen storage capacity by 2030 [41]. Germany is likely to be the main UHS hub where hydrogen can be stored in the most cost-effective way, because of its current underground gas storage capacity and favourable geology. This can provide flexibility to other countries with less suitable geology for UHS in an integrated gas market.

Hydrogen production plans

National Hydrogen Strategy [2] of Germany has outlined various targets related to hydrogen economy to be achieved by 2030, of which one is to increase electrolysis capacity for hydrogen production to at least **10 GW** by **2030** to ensure sufficient availability of hydrogen and its derivates, with the remaining demand covered by imports.

The data collection on hydrogen production plans has focused on the North-East Germany, where the Connected Valley promoted in BalticSeaH2 will be located. Based on data collection conducted in BalticSeaH2, many hydrogen projects in varying degrees of maturity are currently in development in the region, with total estimated electrolyzer capacity of up to **2.3 GWe** by 2030.

Based on publicly provided estimates of the annual hydrogen production volumes (kt/a) of the projects and assuming a 65% electrolyzer efficiency and year-round operational availability for projects that have only provided information of the expected electrolyzer capacity (MW), the planned hydrogen production volume in North-East Germany would be above **210 kt/a** by 2030. To compare, the hydrogen demand in the entire Germany was 1 740 kt/a in 2022 [42].

In the Figure 12 below, the planned projects are categorized geographically, with the size of the spheres indicating the reported or estimated hydrogen production capacity of each project.

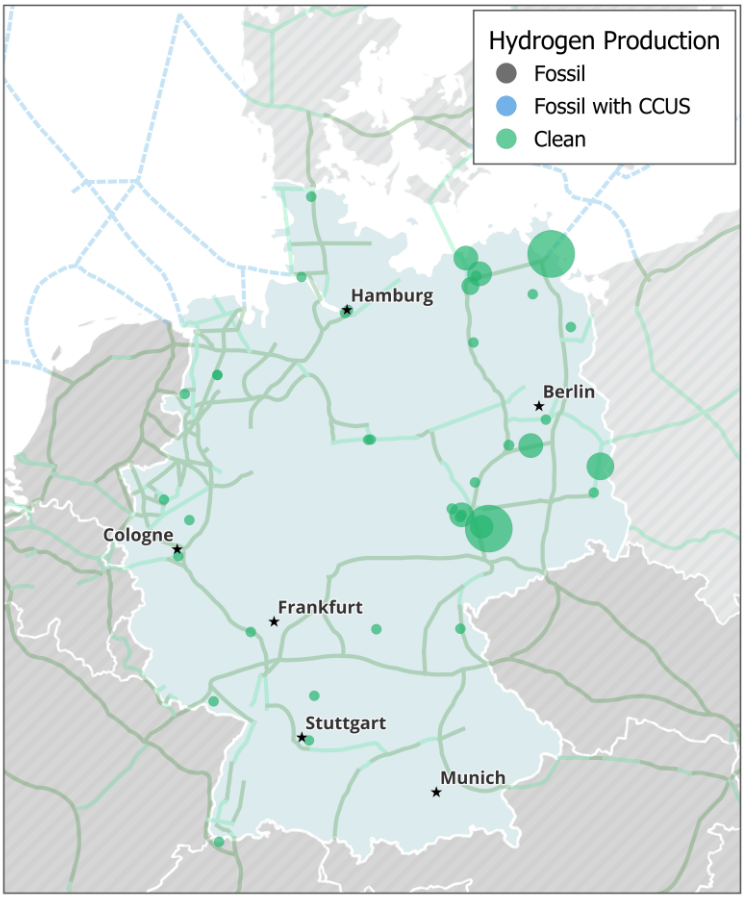

Figure 12. Announced hydrogen production plans (excluding fossil-based production). Facilities with unspecified capacity indicated by triangle markers.

An example of a large-scale clean hydrogen project under construction in the North-East Germany is the **Bad Lauchstädt Energy Park project**, in which a real-life laboratory for the entire clean hydrogen value chain on an industrial scale is built [43]. Hydrogen is produced via a **30 MW** electrolyzer with electricity derived from a nearby wind power park. The produced hydrogen is then stored in underground salt cavern totaling 50 Mm^3 of hydrogen storage capacity, repurposed from a former natural gas cavern storage facility. Additionally, the site is linked to a hydrogen pipeline network previously utilized for natural gas transportation. First, the main end-users for hydrogen are the chemical industries located at the Leuna industrial site. The project aims to identify new consumers for clean hydrogen as the projects proceeds, particularly in mobility and energy sectors.

In addition to clean hydrogen, Germany is also interested in hydrogen production with carbon capture for several reasons. The established infrastructure and expertise in natural gas extraction and processing can facilitate the way for a smoother and more cost-effective transition to a clean hydrogen-based economy while enabling emissions reductions. The existing infrastructure can support the transition period allowing the utilization of existing infrastructure and expertise while clean hydrogen technologies are being scaled up. Additionally, it contributes to the stability and security of supply, as clean hydrogen alone may not be sufficient to meet the demand, especially in the initial phase. Moreover, hydrogen production with carbon capture can present a more economically viable solution in the short to medium term compared to clean hydrogen production.

Potential geographical areas for hydrogen development

Lower Saxony as well as **Mecklenburg-Vorpommern** play a crucial role in the plans for the hydrogen core network in Germany, with key responsibilities in imports, hydrogen production in the North and Baltic Seas, and storage utilization. Various hydrogen projects are taking place in Lower Saxony and Mecklenburg-Vorpommern, also with focus on hydrogen transport and infrastructure. The planned transmission network emphasizes numerous pipelines in Lower Saxony to connect major consumption centres, coastal hydrogen injection points, hydrogen storage facilities, hydrogen production and border crossings.

Education and employment

Multiple universities and other educational institutions offer education related to hydrogen technologies. Primarily within the engineering or environmental sciences discipline, the following programs include hydrogen-related courses:

Wilhelm Büchner University:

- Distance learning program in Hydrogen Technologies.

THWS Schweinfurt:

- Hydrogen Technology (BSc. of Engineering).

Hochschule Aalen (Aalen University):

- Materialography - New Materials, with a focus on hydrogen-related courses.

Hochschule Zwickau (Zwickau University of Applied Sciences):

- Automotive Engineering, including hydrogen-related courses.

Hochschule Emden/Leer:

- Chemical Engineering/Environmental Engineering, with a curriculum covering hydrogen-related topics.

TU Dresden (Dresden University of Technology):

- Master's program in Regenerative Energy Systems.
- Master's program in Hydrogen Technology and Economics.

TAE Esslingen (Technische Akademie Esslingen):

- Master's program in Hydrogen Technology and Economics (part-time).

Technische Hochschule Ingolstadt (Ingolstadt University of Applied Sciences):

- Master of Engineering in Hydrogen Technology and Economics.

Technische Hochschule Rosenheim (Rosenheim University of Applied Sciences):

- Master's program in Hydrogen Technology.

Hochschule Heilbronn:

- Master's program in Hydrogen and Fuel Cell Technology (part-time).

Similar Programs:

- Energy Engineering (122 programs)
- Energy Economics (26 programs)
- General Engineering (87 programs)
- Mechanical Engineering (517 programs)
- Environmental Engineering/Environmental Sciences (153 programs)

These programs offer a comprehensive educational pathway, blending traditional engineering disciplines with a specific focus on hydrogen technologies and their applications.

Upskilling and reskilling of existing workforce is provided by, for example:

Heinze Academy offers online training in hydrogen, available in full-time or part-time formats.

TÜV NORD AG conducts seminars on energy management for individuals interested in reskilling

VDI Wissensforum provides continuing education in the field of renewable energies

Fraunhofer IST offers certificate programs such as "Expert in Hydrogen" and "Practical Knowledge for Hydrogen Projects."

Fit4H2 - Production of Hydrogen Systems covers electrolyzers and fuel cells; aimed at professionals involved in hydrogen production

Hydrogen Training by the Institute for Vocational Education IBB offers comprehensive hydrogen-related training programs.

The workforce requirements in the hydrogen sector highlight several key trends and challenges. Anticipated shortages of IT experts for eco-friendly technology development are expected, particularly affecting sectors like motor vehicle manufacturing and automotive trade. Conversely, increased labor demand is projected in construction and associated architectural and engineering firms due to investments in hydrogen infrastructure and renewable energies. Addressing these needs necessitates a rise in education and training offerings to meet the demands of the evolving hydrogen economy, especially as shortages in skilled professionals and leadership roles loom amid demographic changes. Mitigation strategies involve investing in training programs for technical and managerial positions, targeting profiles such as technical systems planners, plant mechanics, mechatronics specialists, chemical technicians, electronics technicians for automation technology, and safety and security specialists.

Regions with structural weaknesses, including those undergoing coal phase-out, show significant potential for hydrogen economies. This presents opportunities for economic development, particularly in Eastern Germany, which faces high unemployment rates. Notably, four regions stand out for favorable conditions: Northern Germany, Berlin-Brandenburg-Lausitz, Central Germany, and North Rhine-Westphalia, including the Rheinish mining district and the Ruhr area. [44]

Public awareness and social acceptance

The successful implementation of socio-technical transitions, such as the clean hydrogen transition, rely heavily on social acceptance. Social acceptance is commonly defined and studied through the intersection of three types of acceptance: 1) socio-political acceptance (public, policymakers), 2) market acceptance (key industry stakeholders, investors, end-users), and 3) community acceptance (host communities). Social acceptance, in turn, is detrimentally linked with social awareness: the degree to which the public is aware of the existence, purposes, impacts and implications of a technology. Both social acceptance and social awareness are key considerations to mitigate conflicts related to the adoption of new technologies, and in ensuring that related burdens and benefits are distributed evenly within the society.

The Baltic Sea region demonstrates a complex landscape of social acceptance towards the hydrogen economy. At a broader level, there is strong socio-political acceptance driven by concerns over climate change, energy security, and a strong commitment from European and national governments towards decarbonization [45]. The Russian invasion of Ukraine has further amplified the public and political sentiments towards gaining energy independence and investing in renewable energy, translating in some countries (e.g., Finland) also as higher support to nuclear energy [46]. Recent survey [47] also indicates rather high public awareness of hydrogen energy (82% on European level), although awareness of the use of hydrogen specifically in industry settings is lower, on average 56% in Europe. In addition, public acceptance of hydrogen technologies is likely to decrease when it comes to large-scale infrastructure [48]. The rise of right-wing politics and growing “greenlash” against the European environmental agenda, could potentially undermine socio-political support and create challenges for the hydrogen economy's widespread adoption and implementation in the region [49].

Another barrier potential barrier stems from a community-rejection (sometimes referred to as the NIMBY-effect, “Not In My Backyard”), which can hamper the development and deployment of hydrogen facilities, storages, and distribution infrastructure, as well as related wind and solar power placements. For instance, local opposition to wind power plants has become significant in the Baltic Sea region, stemming from concerns over environmental costs and biodiversity loss, noise and visual disturbance, place identity, place-technology-fit, and perceived threats to property value and other industries [50], [51], [52], [53], [54]. Another driver of local opposition is the lack of meaningful community engagement and ownership mechanisms; although participatory elements in spatial planning processes are common in the Baltic Sea region, the participatory processes themselves do not by default prevent conflict, nor solve conflict that arises from new infrastructural or industry development. Denmark remains the sole country in the Baltic Sea region with national legislation on community ownership of renewable energy (the Danish Renewable Energy Act), stating that an approximate of 52% of wind power must be communally owned in Denmark [55].

The success of this community ownership model in driving Denmark's wind power development offers a promising solution to tackle potential hydrogen-related local conflicts in other Baltic Sea region countries. In other words, investigating community perspectives and including affected communities in the development and deployment of the hydrogen transition can effectively prevent conflict and opposition. Engaging with diverse members of the public (in terms of gender, age, etc.) can also give a wider understanding of the sources of concerns over hydrogen technologies and provide means to overcome these concerns. For instance, several research outputs [47], [48] indicate that women are more critical towards hydrogen technologies and have more frequently concerns over their sustainability and safety, thus indicating a need to target women more effectively in awareness-raising and engagement activities.

Although literature on social aspects of hydrogen economies is still scarce, Germany is among the most researched contexts for the socio-political acceptance and awareness of hydrogen technologies. In the German context, land and infrastructure availability were identified as key questions for hydrogen acceptance [56]. The importance of land use questions is also further emphasized due to the growing resistance to wind power projects, with over 660 active citizen initiatives oppose wind power projects in Germany [50]. According to the industry group German Wind Energy Association (BWE), growing resistance to new projects has become a veritable challenge for keeping wind power expansion in line with emissions reduction goals [50]. On the other hand, wind power enjoys high public acceptance in Germany, and concerns over climate change are among the highest in Europe [45].

Literature paints divisive light on the state of hydrogen awareness, with some suggesting hydrogen awareness is as low as 60% in Germany, and some as high as 90%.

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