VEPE

Vetytalous Etelä-Pohjanmaalla
Hydrogen economy in South Ostrobothnia

VEPE project WP3 Potential hydrogen value chain in South Ostrobothnia and Value Chain Technical and Economic Analysis (T3.1 and T3.2)

Giovanna Andrea Pinilla De La Cruz
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ABSTRACT

This study addresses tasks T3.1 (Identification of the clean hydrogen value chain) and T3.2 (Technical and economic analysis of the value chain) of work package 3 of the VEPE project, with the aim of identifying value creation opportunities aligned with regional industrial characteristics and assessing the technical and economic feasibility of value chain integration.

Notably, this report situates the regional opportunities within the broader context of European and Finnish hydrogen policy, highlighting its role in decarbonising hard-to-decarbonise sectors and the current gap between the supply and demand of clean hydrogen. Following a comparative assessment of alternative hydrogen value chains, clean ammonia production emerges as the most promising option for South Ostrobothnia, based on a combination of empirical data collection as well as national and international literature. Here, decentralised small-scale hydrogen-to-ammonia systems appear as suitable configurations with great potential for the region given its significant renewable energy potential, substantial agricultural and agri-food activity, and strategic importance for fertilizer production and emerging marine fuel markets. The report outlines the production, transport, and distribution segments of this value chain and analyses key factors such as the availability of renewable electricity, water resources, production technologies, and logistics infrastructure.

A techno-economic analysis of a small-scale pilot plant indicates that, while costs remain above current market levels, primarily due to limited economies of scale and challenges of greenfield projects in clean ammonia, such a setup could provide valuable learning opportunities, reduce integration risks, and facilitate future production scaling. The results underscore the need to leverage learning curves by implementing small-scale pilot projects as initial steps, with coordinated stakeholder involvement, to drive the transition to a regional clean hydrogen economy.

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1 WP 3: Potential hydrogen value chains in South Ostrobothnia

1.1 Scope of the analysis

This report has been prepared as part of the VEPE project related to the work package 3 (T3.1 and T3.2). The project has been financed by the European Regional Development Fund (ERDF), Regional Council of South Ostrobothnia, University of Vaasa, and Seinäjoki University of Applied Sciences. The scope of this report is related to tasks T3.1 “Identification of the Clean Hydrogen Value Chain” and T3.2 “Value Chain Technical and Economic Analysis”. Regarding the results of T3.3, on the “Capabilities related to the implementation of the value chain, skills and training needs,” those are released on a separate report prepared by SEAMK.

In particular, T3.1, “Identification of the Clean Hydrogen Value Chain,” addresses the identification of a clean hydrogen value chain that corresponds to the region's characteristics and industrial structure, and that has the potential to generate value. This analysis includes the study of commercial activities in each segment of the value chain, from production to application and end-use possibilities, and the types of actors that would be involved. Regarding the naming of the specific actors identified in the development of the work in relation to the segments of the value chain, this information is not included in this report for data protection reasons, but it has been provided in the steering group meetings during the implementation of this project.

In T3.2 “Value Chain Technical and Economic Analysis,” a techno-economic analysis was carried out for the selected clean hydrogen value chain based on a small-scale plant configuration. This analysis was focused on the potential investment and infrastructure needs for the value chain integration.

1.2 Methodology

The data collection sources for this study consisted of primary sources, such as workshops and semi-structured interviews with key stakeholders, especially for the identification of the value chain, as well as secondary sources, such as public documents, relevant national and international reports on the topic, academic articles, and websites of reputable organizations. Furthermore, the results of work packages 1 and 2 were also considered in this study. Additionally, estimations in the techno-economic analysis are based on the latest reports on the field.

2 Identification of the clean hydrogen value chain

Identifying the most suitable hydrogen value chain for the South Ostrobothnia region is a critical step in boosting the regional hydrogen economy, as this decision will define the strategic vision and development pathways for its future growth. This task required the development of a comprehensive and updated contextual framework to ensure a deep understanding of the problem at the micro, meso, and macro levels.

From a global perspective at the macro level, the urgent need to move forward with a strong response to climate change is evident. Reducing greenhouse gas emissions by decarbonising major economic activities is a key issue on government agendas worldwide. Following the Paris Agreement, the International Energy Agency defines scenarios that are regularly updated to establish clear pathways for responding to climate change (IEA - International Energy Agency, 2025). In the net-zero emissions (NZE) scenario, the goal is to limit the temperature increase to less than 1.5°C if we achieve zero emissions in energy systems by 2050. This is undoubtedly ambitious, but it provides a roadmap for countries to implement national programmes and setting goals (IEA - International Energy Agency, 2025).

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At the European national level, numerous efforts over the past few years have focused on decarbonising energy systems, for example, through direct electrification that integrates renewable energy sources, such as wind and solar photovoltaics, as well as electric vehicles and household appliances. However, some industries pose a challenge to electrification and decarbonisation, known as "hard-to-abate" sectors, where indirect electrification is required; one option is clean hydrogen (Sosa et al., 2025). In the NZE scenario proposed by the International Energy Agency, hydrogen will represent 2% of total final consumption in 2035, a figure that will increase to almost 10% in 2050 (IEA - International Energy Agency, 2025). Under this scenario, clean hydrogen and its derivatives are expected to increase their share in hard-to-abate sectors, such as the chemical industry (including fertilizers), steel, aviation (eSAF), and maritime transport (ammonia, ethane, ethanol, and pure hydrogen).

Hydrogen use in Europe is dominated by refining, which accounts for almost 60% of demand, followed by clean ammonia production at around 25%, while other chemical processes and applications represent approximately 10% to 15% (Clean Hydrogen Joint Undertaking, 2025). In Europe, hydrogen demand reached approximately 7.8 million tonnes in 2024, of which only about 36 000 tonnes were supplied by clean hydrogen. By May 2025, the cumulative installed capacity of electrolysers in Europe had reached around 10 GW (Clean Hydrogen Joint Undertaking, 2025). While this represents a significant improvement over previous years, it is still clearly insufficient to meet current demand.

The total decarbonisation of hydrogen value chain looks challenging now, as replacing current high-carbon hydrogen production would require drastically increasing clean hydrogen production, when costs are not yet competitive and some clean hydrogen projects face difficulties in appearing viable (Energy Sector Management Assistance Program (ESMAP) et al., 2023). Currently, European policies such as the REDIII directive, FuelEU Maritime and ReFuelEU Aviation are pushing forward the hydrogen demand by encouraging domestic production development and demand in hard-to-abate sectors, but the implementation of regulatory targets are slow across European countries. Furthermore, for the full implementation of key policy instruments, it is necessary to enhance funding mechanisms, develop a strong clean hydrogen market, fully implement the lead markets, and provide the necessary infrastructure (Aisling Deasy-Millar et al., 2025).

Concerning Finland at the meso level, the country has all the essential strengths needed to build a successful hydrogen economy and benefit from its expansion in the coming decades. Starting with a clean and reliable electrical system, and a great potential for renewable energy and abundant natural resources, Finland has extensive industrial experience in areas that will supply and use hydrogen solutions. The country also boasts an exceptional natural resource base that supports hydrogen production and the creation of derivative products. Besides abundant renewable energy sources, biogenic carbon dioxide, and a wide range of metals such as copper, zinc, nickel, aluminium, iron, gold, platinum, cobalt, and lithium. These materials are essential to produce hydrogen-related products, such as synthetic fuels and clean steel, as well as for the necessary equipment throughout the supply chain. The HydrogenCluster Finland (2023), emphasized on the need to boost the growth of the domestic hydrogen production industry, strengthen local industries, and export hydrogen-related solutions to unlock economic growth opportunities.

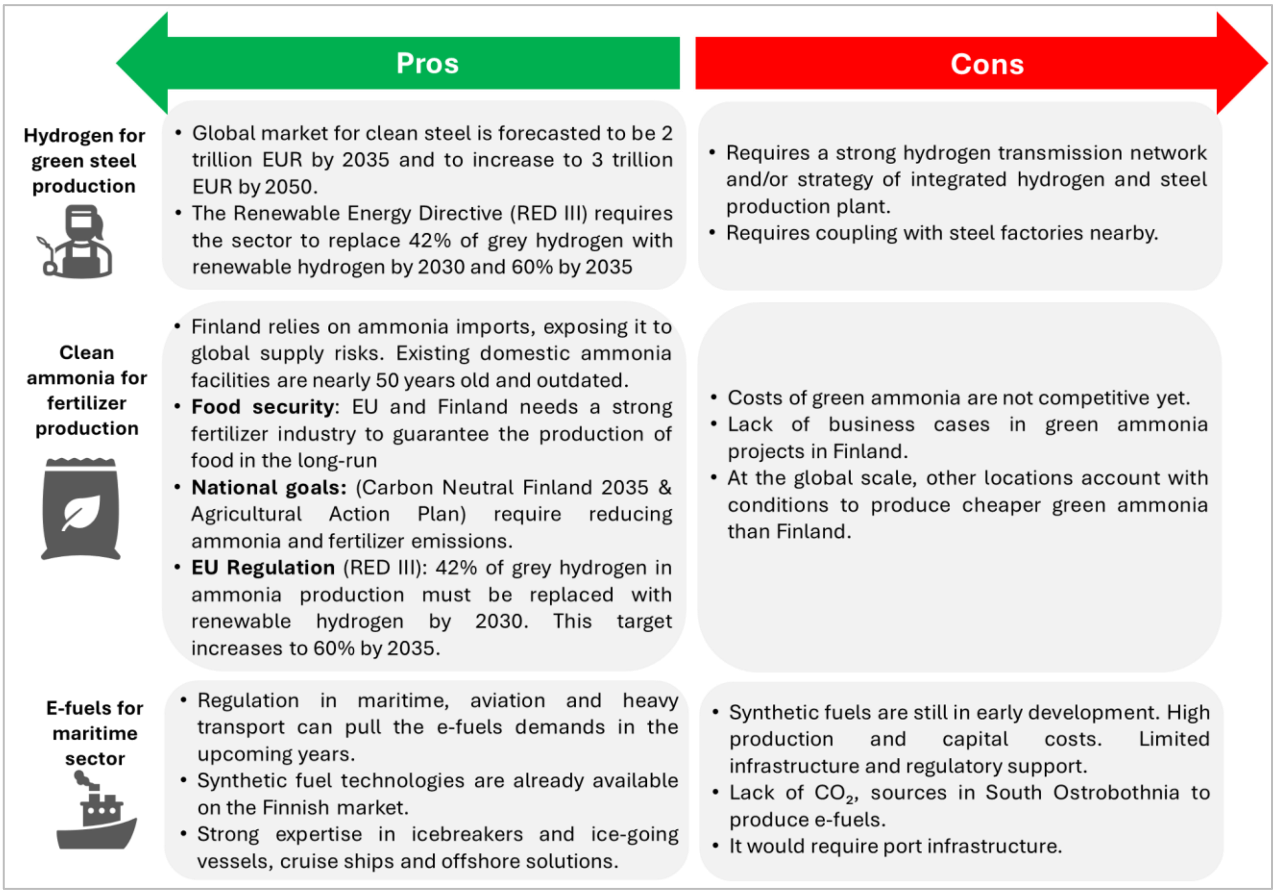
In the micro level, since renewable energy potential is widespread throughout the country, investment and production could be enhanced in both the northern and southern regions (Hydrogen Cluster Finland, 2023). For example, the South Ostrobothnia region leads the way in terms of the cumulative capacity of wind and solar photovoltaic projects in various stages of development, with more than 9.6 GW (Renewables Finland & Ramboll, 2025, 2026). This is a remarkable advantage in the race for decarbonisation through the development of the hydrogen economy and possesses many benefits to improve overall security and resilience (Hydrogen Cluster Finland, 2023). Therefore, the identification of clean hydrogen value chain according to the industrial characteristics of the region would pay the way for further investments and developments.

2.1 Identification and selection of a clean hydrogen value chain in South Ostrobothnia

National reports indicate that Finnish industry should develop and focus on decarbonising hard-to-abate sectors, such as the steel industry, transportation (especially maritime and aviation), and the chemical industry, for example, clean ammonia production for fertilisers production (Frost and Sullivan, 2022; Hydrogen Cluster Finland, 2023; Laurikko et al., 2020).

Furthermore, results from the VEPE project WP 1 indicate that the agricultural sector could benefit from the development of clean hydrogen, and in particular, clean ammonia to produce low-carbon fertilizers (Siekkinen, 2024). Similarly, the report of WP1 indicates that the logistics sector could benefit, where hydrogen could be converted into fuels for the maritime sector, such as clean ammonia and/or e-methanol. Regarding the WP2-WP3 workshop in March 2025, participants identified potential opportunities to produce hydrogen derivatives such as e-methane, e-methanol, clean ammonia, and liquefied biogas (Pinilla-de La Cruz, 2026).

Overall, three hydrogen value chains appear with greater potential in Finland according to national studies and partial results of this project as a: **i) hydrogen for the steel sector, ii) clean ammonia to produce low-carbon fertilizers, and ii) e-fuels for shipping industry**. A comparative analysis of these three potential value chains based on technology maturity, regulatory drivers, and opportunities is presented in Figure 1.



	Pros	Cons
Hydrogen for green steel production	• Global market for clean steel is forecasted to be 2 trillion EUR by 2035 and to increase to 3 trillion EUR by 2050. • The Renewable Energy Directive (RED III) requires the sector to replace 42% of grey hydrogen with renewable hydrogen by 2030 and 60% by 2035	• Requires a strong hydrogen transmission network and/or strategy of integrated hydrogen and steel production plant. • Requires coupling with steel factories nearby.
Clean ammonia for fertilizer production	• Finland relies on ammonia imports, exposing it to global supply risks. Existing domestic ammonia facilities are nearly 50 years old and outdated. • **Food security**: EU and Finland needs a strong fertilizer industry to guarantee the production of food in the long-run • **National goals:** (Carbon Neutral Finland 2035 & Agricultural Action Plan) require reducing ammonia and fertilizer emissions. • **EU Regulation** (RED III): 42% of grey hydrogen in ammonia production must be replaced with renewable hydrogen by 2030. This target increases to 60% by 2035.	• Costs of green ammonia are not competitive yet. • Lack of business cases in green ammonia projects in Finland. • At the global scale, other locations account with conditions to produce cheaper green ammonia than Finland.
E-fuels for maritime sector	• Regulation in maritime, aviation and heavy transport can pull the e-fuels demands in the upcoming years. • Synthetic fuel technologies are already available on the Finnish market. • Strong expertise in icebreakers and ice-going vessels, cruise ships and offshore solutions.	• Synthetic fuels are still in early development. High production and capital costs. Limited infrastructure and regulatory support. • Lack of CO_2, sources in South Ostrobothnia to produce e-fuels. • It would require port infrastructure.

Figure 1. Analysis of pros and cons of three hydrogen value chains. Based on Bonnet-Cantalloube et al. (2023; Frost and Sullivan (2022), Guidehouse Netherlands B.V. (2023), Hydrogen Cluster Finland (2023), and Laurikko et al. (2020)

The next step in this analysis was to select the value chain with the greatest potential to generate value for South Ostrobothnia, based on the region's industrial characteristics. To this end, the three previously mentioned value chains were analysed to better understand the regional characteristics in relation to key aspects of hydrogen production and commercialisation as: location of major renewable energy sources, electricity grids, hydrogen transmission/distribution networks, geographical location of potential demand and supply hubs, enabling infrastructure, carbon dioxide availability, and existing industries and expertise (Table 1).

Table 1. Analysis of the three value chains according to the regional characteristics of South Ostrobothnia

Regional features	Value chains		
Criteria	**Hydrogen for Steel sector**	**E-fuels for shipping**	**Clean ammonia for fertilizers**
Location of renewable energy sources	A large number of electricity projects, widely distributed throughout the region.	A large number of electricity projects, widely distributed throughout the region.	A large number of electricity projects, widely distributed throughout the region.
Electricity grids	The region is well connected and has robust electrical networks providing grid stability.	The region is well connected and has robust electrical networks providing grid stability.	The region is well connected and has robust electrical networks providing grid stability.
Hydrogen transmission/distribution networks	Not current plans for South Ostrobothnia. Need for distribution or transmission hydrogen networks.	Not current plans for South Ostrobothnia. Need for distribution or transmission hydrogen networks in case of large-scale e-fuel production. Not compulsory for small-scale production.	No need for domestic production and demand. Need for distribution or transmission hydrogen networks in case of large-scale clean ammonia production. Not included in current plans for southern Ostrobothnia.
Geographical location of potential demand and supply hubs	Potential demand centres for hydrogen for use in steel production are located outside the region.	Potential demand centres for e-fuels in maritime sector are located outside the region. It is expected that industrial hubs in e-fuels will be located close to the seaports.	Strong agriculture tradition in the region, with a great potential for use of fertilizers by domestic industry.
Enabling infrastructure (ports, roads, railways, etc.)	Need for enabling infrastructure, especially railways and roads. The region is well connected.	Need for enabling infrastructure, especially seaports. The region does not have access to sea waters.	Need for enabling infrastructure, especially railways and roads.
Water availability	Need for significant amount of water for hydrogen production.	Need for significant amount of water for hydrogen production.	Need for significant amount of water for hydrogen production.
CO_2 availability	No specific need for carbon dioxide availability.	Significant amounts of CO_2 are needed for hydrogen synthesis into e-fuels. Not need of CO_2 for clean ammonia.	It depends on the nitrogen fertilizer to produce. Urea production requires carbon dioxide availability. Other types of N-fertilizers such as ammonium nitrate, calcium ammonium nitrate, ammonium phosphate, diammonium phosphate or ammonium sulphate appear as potential alternatives.
Industries and expertise	Few industries related to the metal industry located in the region. Gap in industries and expertise in hydrogen.	No relevant industries related to the maritime sector located in the region. Gap in industries and expertise in hydrogen and e-fuels.	Expertise in end-use, particularly in agriculture sector. Gap in industries and expertise in hydrogen and clean ammonia.

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Results of analysis indicate that the value chain with higher connection with the regional economic activities and high potential for value creation and value capture is the hydrogen-to-ammonia production, with focus on the fertilisers production. Currently, South Ostrobothnia produces approximately 12% of the total value of the national food industry. Furthermore, this industry is well-positioned to adapt local production to the evolving needs of farmers through cooperation along local value chains. Therefore, the potential for value creation for regional stakeholders is significant if the value chain is successfully integrated with the agricultural and food sectors. According to the Hydrogen Cluster Finland (2023), Finland relies on imported ammonia, which exposes it to fluctuations in the global market. Domestic ammonia production facilities are aging, necessitating their modernization the demand for fertilizers will continue to rise. Therefore, developing clean ammonia production would strengthen Finland's security of supply, reduce dependence on external sources, and support national climate goals, including those outlined in the Finland Carbon Neutral 2035 plan and the Agricultural Action Plan.

2.1.1 Opportunities from decentralised small-scale ammonia production

Nowadays, ammonia supply relies primarily on conventional grey ammonia, produced in large-scale, centralized facilities using natural gas via steam methane reforming (SMR). However, recent geopolitical dynamics have led to considerable volatility in natural gas prices since 2021, resulting in a remarkable increase in ammonia prices, from 85–500 EUR per tonne to 850–980 EUR per tonne (Sandalow et al., 2022; World Bank and ESMAP, 2025). In this context, transportation and distribution costs are becoming increasingly significant and are likely to similarly impact the supply of low-carbon alternatives, such as blue ammonia.

For regions like South Ostrobothnia, the exploration of **small-scale decentralised ammonia production systems** offers a promising alternative to reduce the carbon footprint and, at the same time, address the challenge of high volatility in the fertilizer market and strength regional resilience (Alho et al., 2024; Kirk et al., 2024; Sosa et al., 2025). Decentralised ammonia production corresponds to small-scale plants located close to the place of use, with annual production between 400 and 18 250 tonnes per year and 1-10 MW of electrolysis capacity (Alho et al., 2024; Miltrup, 2025). While these systems may initially involve higher costs, primarily due to infrastructure and value chain integration, they can generate economic benefits in the medium and long term by shortening supply chains and aligning production more closely with local demand (Alho et al., 2024; Kirk et al., 2024).

Likewise, decentralised systems mitigate the risk of natural gas price volatility, as electricity becomes the primary input (Kirk et al., 2024). This shift improves security of supply and contributes to greater price stability. Looking ahead, the cost of grey ammonia, including transport and carbon pricing, is projected to reach approximately 986 EUR per ton in 2030 and 1 444 EUR per ton in 2050 (Sosa et al., 2025). For large-scale clean ammonia production (including transport), costs are expected to be around 955 EUR per ton in 2030, decreasing to 737 EUR per ton in 2050. In contrast, small-scale, decentralised clean ammonia production is estimated to cost around 1 541 EUR per ton in 2030, decreasing to 984 per ton in 2050 as the technology matures and system-level economies of scale improve (Sosa et al., 2025).

In addition to the potential long-round cost benefits, the development of small-scale decentralised ammonia production can produce other benefits such as encouraging work in cooperative schemes where a greater number of actors can participate in innovative business models that result in the capture and retention of money among local and regional actors, as well as the creation of new skills in the area of influence of these initiatives (Kirk et al., 2024).

2.1.2 Emerging markets

Beyond the use of clean ammonia in fertilizer production, there are interesting opportunities emerging from the shipping industry as a complementary solution. Ammonia is expected to play a significant role in the maritime sector's transition away from fossil fuels. Given Finland's long tradition, experience, and industrial capabilities in maritime technologies and shipping, the development and adoption of ammonia as a marine fuel represents a promising opportunity for the country and South Ostrobothnia region. IRENA's projected scenarios for clean ammonia in 2050 place the fertilizer industry first in production, followed by maritime transport with 29% and the use of clean ammonia as a hydrogen carrier with 18%, and to a lesser extent in other uses (10%) and in power generation with 4% (Fichtner, 2025; IRENA & AEM, 2022; IRENA, 2022).

2.2 Analysis of value chain segments

After selecting the value chain for analysis in South Ostrobothnia, the next step corresponded to identify the composition of the upstream, midstream, and downstream segments (Figure 2). In this case, the upstream segment includes processes prior to the production of hydrogen to clean ammonia, such as renewable energy generation and water supply for hydrogen production. The midstream segment encompasses hydrogen production, clean ammonia synthesis, and the processes of transport, storage, and compression. Finally, the downstream segment includes the potential applications of the product, such as the production of fertilizers for the food and agriculture industries, and opportunities in the shipping industry as a low-carbon fuel.

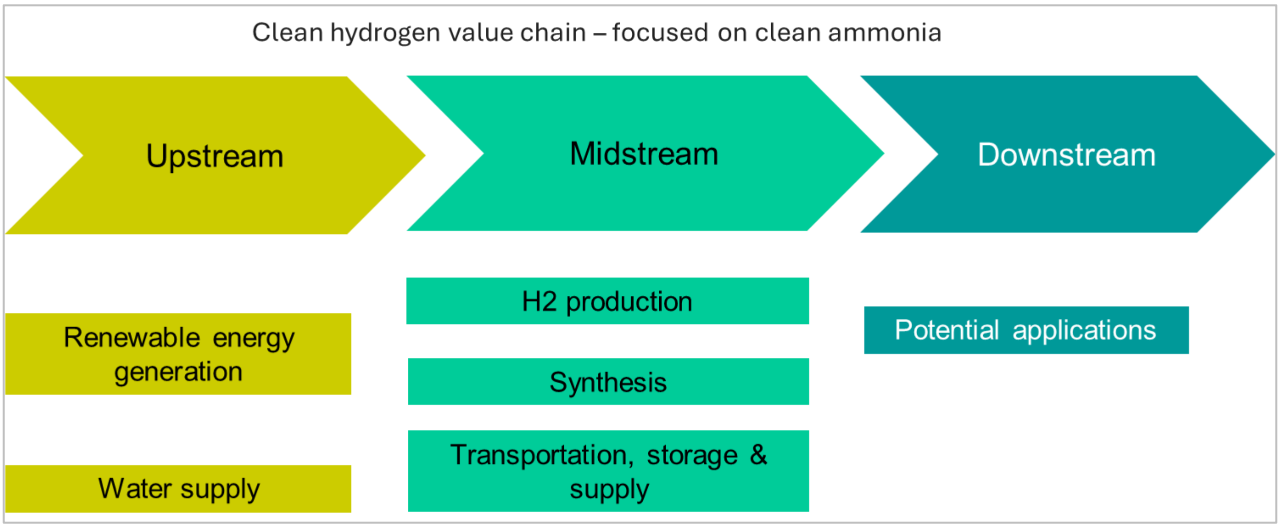


Figure 2. Clean hydrogen value chain by segments focused on clean ammonia

2.2.1 Upstream

- **Renewable energy**

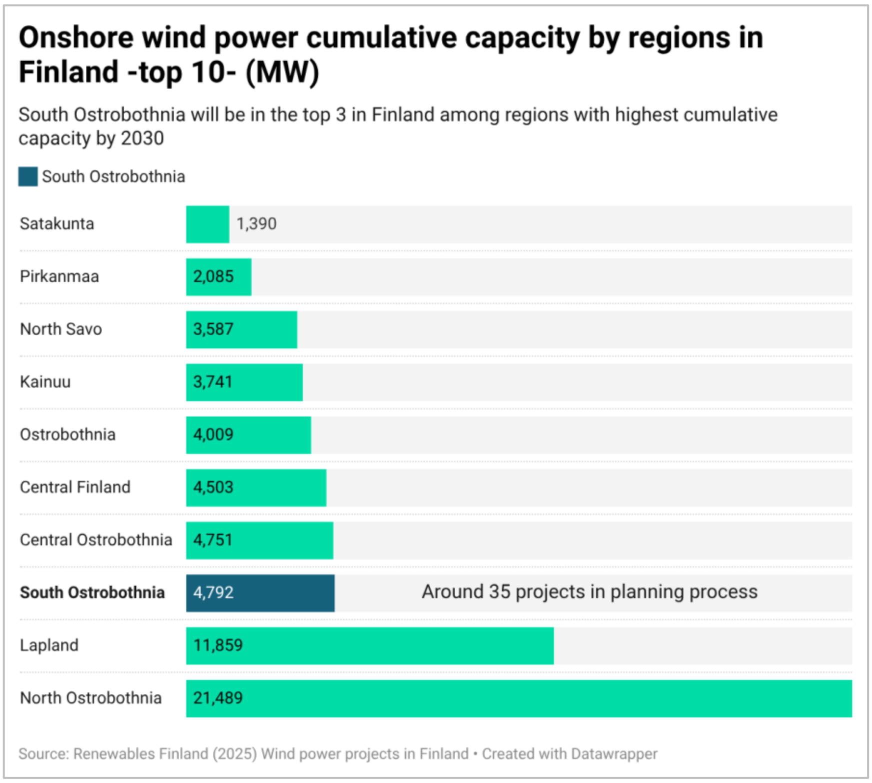
Hydrogen production is highly dependent on the availability of renewable energy, as it requires significant amounts of electricity (50-56 kWh per kg of hydrogen). Therefore, secure supply of electricity for hydrogen production and geographical proximity/and or transmission lines are crucial for the development of hydrogen infrastructure and cost competitiveness (Hydrogen Cluster Finland, 2023). Grid stability is also essential for hydrogen production to support continuous operation of adjacent hydrogen-consuming processes (Guidehouse Netherlands B.V., 2023).

Regarding energy resources for hydrogen production, South Ostrobothnia ranks among the top three regions in Finland in terms of cumulative renewable energy capacity under development, with approximately 6.5 GW of wind power projects and 3.1 GW of solar photovoltaic projects in various stages of development (Renewables Finland & Ramboll, 2025, 2026) (Table 2). Additionally, Finland has a robust electricity grid that allows for the seamless integration of new renewable energy sources.

Table 2. Onshore wind power and solar photovoltaic projects in various stages of development in South Ostrobothnia. Based on (Renewables Finland & Ramboll, 2025, 2026)

Renewable energy technology	Project stage of development	Capacity (MW)
Wind power	Operation	1185,5
	Under construction	520
	Planning	4792
	Total wind power	**6497**
Solar PV	Operation	9,3
	Under construction	134
	Planning	2976
	Total solar PV	**3119**
Total cumulative capacity		**9617**

As shown in Figure 3, more than 35 wind energy projects under development (planning) in South Ostrobothnia provide insight into how the region's cumulative capacity will increase in the coming years. Most of these projects will become operational between 2028 and 2030 (Renewables Finland & Ramboll, 2025).



Source: Renewables Finland (2025) Wind power projects in Finland • Created with Datawrapper

Figure 3. Renewable energy cumulative capacity by 2030 in onshore wind power projects in South Ostrobothnia. Based on Renewables Finland & Ramboll (2025)

The current portfolio of solar photovoltaic projects under development in South Ostrobothnia indicates rapid growth potential in the coming years. By 2030, the cumulative capacity of planned new projects is estimated to reach approximately 3 GW, making South Ostrobothnia the second largest region in Finland, after Satakunta, in terms of solar energy development (Renewables Finland & Ramboll, 2026) (Figure 4).

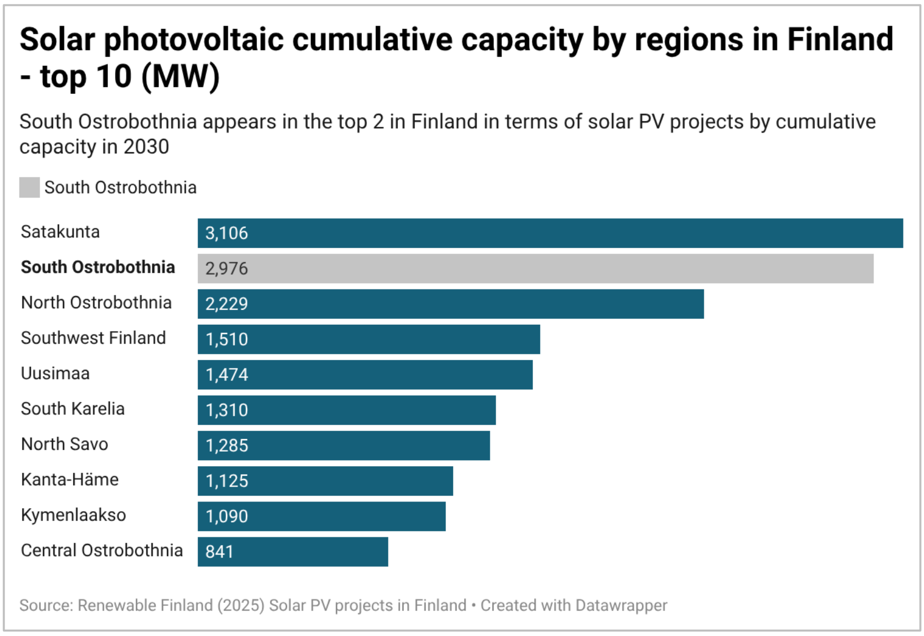


Figure 4. Renewable energy cumulative capacity by 2030 in onshore solar photovoltaic projects in South Ostrobothnia. Based on (Renewables Finland & Ramboll, 2026).

Wind and solar photovoltaic power projects are well-distributed around the region, especially, in two zones/areas, that we identified as potential energy "clusters" (Figure 5). These are: i) **North-east cluster**: Äläjarvi-Vimpeli with around 1.5 GW of cumulative capacity, and ii) **South-west cluster**: Kauhajoki, Isojoki, Teuva, Kurikka and even Seinäjoki with around 5 GW of cumulative capacity. These clusters, or areas where most of the region's major energy projects are concentrated, provide information on potential locations (due to geographical proximity) for the development of the hydrogen industry. It is worth noting that establishing synergies with key players in the value chain, such as the main developers and owners of energy projects in the region, is essential to exploring the possibilities of using electricity in clean hydrogen production projects.

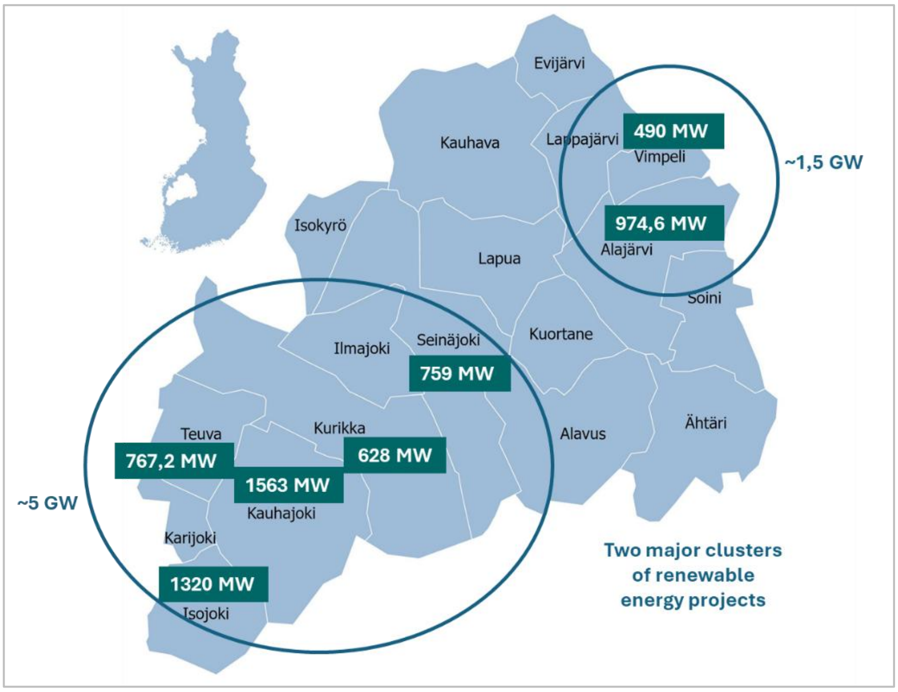
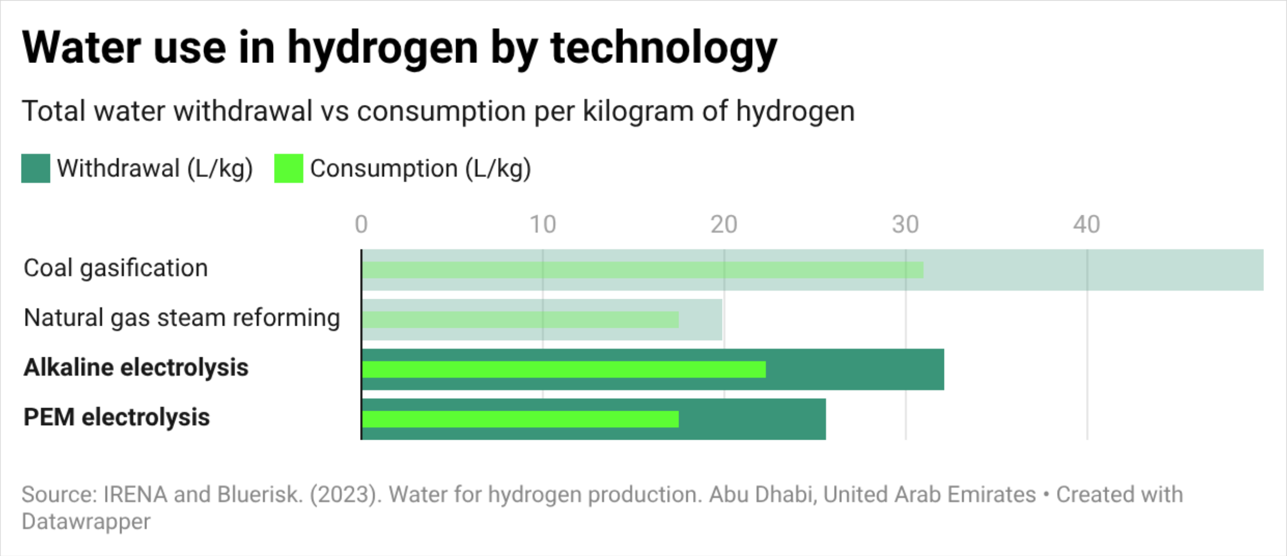


Figure 5. Potential clusters of wind and solar photovoltaic projects in South Ostrobothnia by 2030. Based on Renewables Finland & Ramboll (2025, 2026).

Therefore, considering the significant energy resources in South Ostrobothnia, the future development of decentralised small-scale ammonia plants will be connected by the projected ammonia demand in the region and surrounding areas, in such a way that the capacity of the water electrolysis system matches the market demand (Miltrup, 2025).

- **Water availability:**

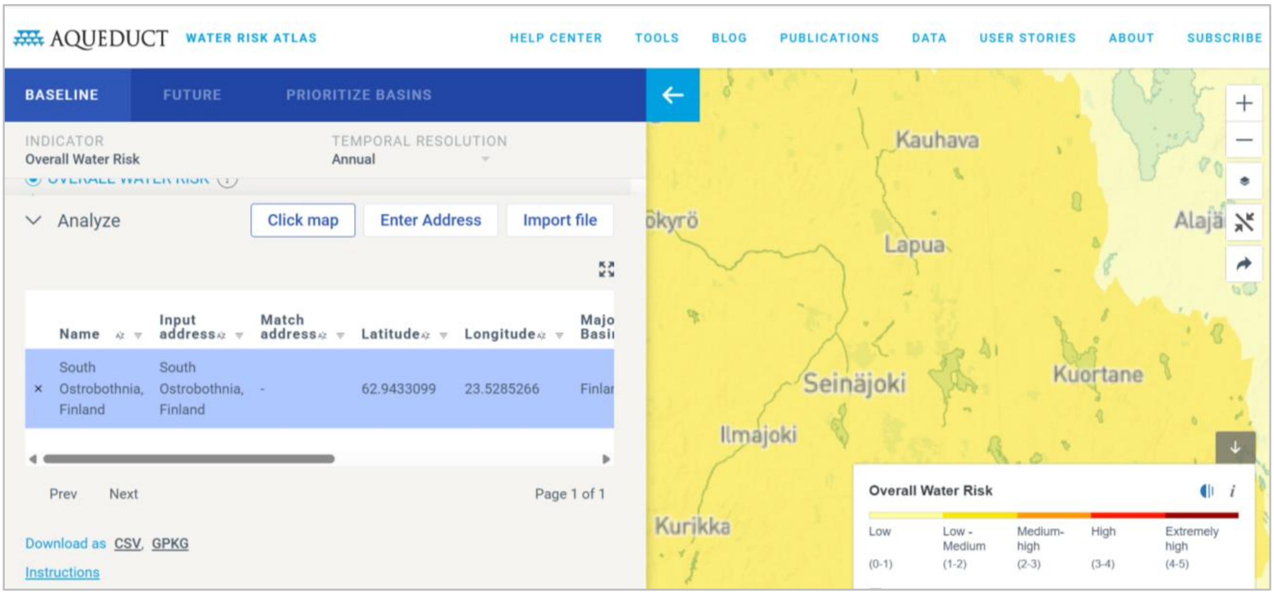
Clean hydrogen production requires substantial amounts of freshwater. From a stoichiometric point of view, the production of one kilogram of hydrogen requires approximately nine kilograms of water. However, in practice, water electrolysis typically requires the use of ultrapure water to ensure efficient operation and prevent damage to the electrolyser system (IRENA, 2020). Therefore, water treatment must be considered when analysing value chain integration. This includes all the necessary pretreatment stages to achieve ultrapure quality, such as pretreatment through filtration, activated carbon, and softening, followed by deionization and final polishing (Roland Berger, 2023). In addition to production water, processing water and cooling water requirements must also be considered. According to estimates from IRENA and Blue Risk, the total water withdrawal for clean hydrogen production via alkaline electrolysis can reach approximately 32.2 litres per kilogram of hydrogen, while proton exchange membrane electrolysis may require approximately 25.7 litres per kilogram (Figure 6). In both cases, around 56 % of the water is used for cooling purposes and 44 % for hydrogen production (IRENA and Bluerisk, 2023). Other studies consider a typical water consumption for electrolysis in a range between 18 and 24 kg of water per kilogram of hydrogen (IRENA, 2020).



Source: IRENA and Bluerisk. (2023). Water for hydrogen production. Abu Dhabi, United Arab Emirates • Created with Datawrapper

Figure 6. Total withdrawal in hydrogen production by technology. Based on IRENA and Bluerisk (2023)

Finland has abundant water resources and expertise in water management, making it easy to supply the necessary volumes without costly treatment (Hydrogen Cluster Finland, 2023). In South Ostrobothnia, data from the online tool “Aqueduct 4.0” indicate that the overall level of water risk is classified as low to medium, depending on the municipality. The northeastern part of the region shows lower overall water risk levels, as illustrated in Figure 7 (Kuzma, 2023). The overall water risk indicator encompasses a wide range of water-related risks by combining selected indicators from the categories of physical quantity, water quality, and regulatory and reputational risk, where higher values indicate greater water risk (Kuzma, 2023).



INDICATOR
Overall Water Risk

TEMPORAL RESOLUTION
Annual

	Name	Input address	Match address	Latitude	Longitude	Majo Basi
×	South Ostrobothnia, Finland	South Ostrobothnia, Finland	-	62.9433099	23.5285266	Finla

Figure 7. Overall water risk indicator of South Ostrobothnia according to online database Aqueduct 4.0 (Kuzma, 2023).

More detailed information about water availability in South Ostrobothnia could be found in one of the reflective articles of the VEPE project called "*Is there enough water for a hydrogen economy in South Ostrobothnia?*" by Lind (2025).

For small-scale ammonia setups, it would be advantageous to implement compact and flexible water supply systems (Miltrup, 2025). Due to the groundwater and inland surface water resources in South Ostrobothnia, these water systems need to be equipped with devices for the removal of metals and minerals, as well as the removal of organic matter and particulate matter in order to provide the required high-pure quality water for electrolysis (Ellis et al., 2000; Miltrup, 2025; Panagopoulus et al., 2019) .

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2.2.2 Midstream

- **Clean hydrogen production**

Low-carbon ammonia is produced using hydrogen generated through water electrolysis. This technology allows for the replacement of natural gas with clean hydrogen. The electrolysis process uses electricity to separate water into hydrogen and oxygen. The chemical reaction for water electrolysis is shown below:

$$2H2O(l) \rightarrow 2H2\ (g) + O2\ (g)$$

Currently, in terms of water electrolysis technologies there are four options in different maturity levels: Alkaline Electrolyser, Proton Exchange Membrane (PEM), Solid Oxide Electrolyser Cell (SOEC), and Anion Exchange Membrane (AEM). Alkaline electrolysis and PEM electrolysis are currently the most widely used technologies and exhibit a high degree of technical maturity, as shown in Figure 8 (Observatorio Tecnológico del Hidrógeno, 2025). Alkaline electrolysis uses metal electrodes immersed in an alkaline liquid electrolyte and has been employed in the industrial production of hydrogen for over 120 years. In contrast, PEM electrolysis operates in an acidic environment and is a more recent technology. It was first applied in military and aerospace contexts during the 1980s and has undergone significant commercial development since 2000 (Fichtner, 2025). Today, a substantial proportion of hydrogen projects in the planning or near implementation phase are based on this technology.

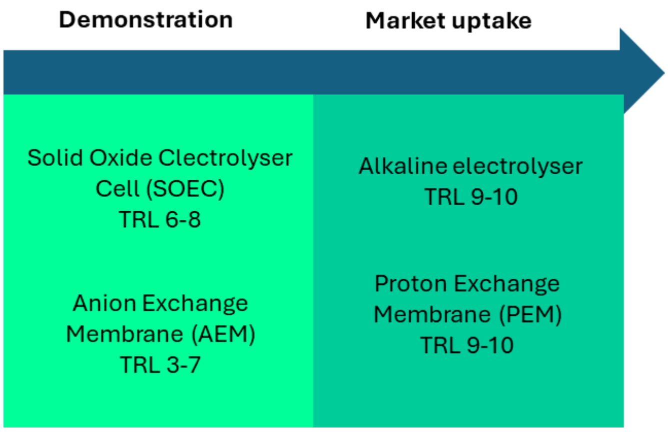

Figure 8. Comparative maturity levels of key electrolysis technologies used for hydrogen production. Based on Observatorio Tecnológico del Hidrógeno (2025)

In terms of hydrogen technology production, the maturity of water electrolysis does not appear as a main bottleneck for the deployment of the hydrogen economy as alkaline and PEM systems are commercially available now. However, flexible operation and energy storage is recommended especially for decentralised small-scale plants. This can be achieved with PEM systems that provide fast response to changes without significant degradation (Miltrup, 2025; Sayed-Ahmed et al., 2024). Regarding the design of water electrolysis systems, commercially available solutions include compact and modular configurations, such as containerized and skid-mounted systems suitable for decentralised small-scale plants (Miltrup, 2025). These designs allow for scalability while offering a high degree of automation, limited maintenance requirements, and robust operational performance (Miltrup, 2025).

In Finland, according to Hydrogen Cluster Finland (2026), there are approximately 59 clean hydrogen projects with a combined electrolyser capacity exceeding 12 000 MW. These projects are distributed throughout the country, with a particularly high concentration in the southern, western, and northwestern regions, but there is not specific clean hydrogen projects located in South Ostrobothnia region (Figure 9).

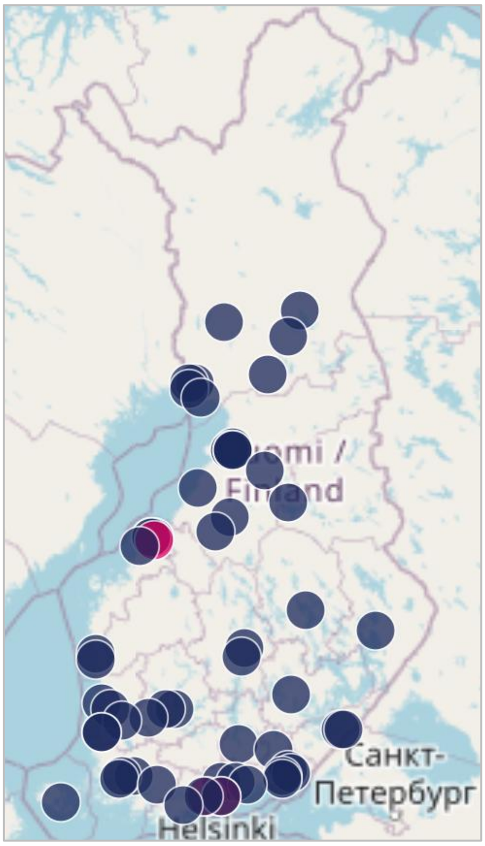

Figure 9. Geographical distribution of clean hydrogen projects in Finland (Hydrogen Cluster Finland, 2026).

The information provided by Hydrogen Cluster Finland in its online public database includes projects at various stages of development across the entire value chain. Currently, only four projects are operational, while the majority are in the planning (44%) and feasibility (31%) stages, with anticipated start dates between 2026 and 2034, as shown in Figure 10 (Hydrogen Cluster Finland, 2026). This situation reflects the current limitations of the global hydrogen market, including the lack of price competitiveness of clean hydrogen compared to fossil fuels and the significant infrastructure investments required. As a result, final investment decisions, and the transition from planning to construction have slowed both globally and in Finland. Therefore, it is crucial that at least some projects, even smaller ones, reach the operational phase. These initial examples can serve as concrete case studies, helping to address technical, commercial, and regulatory challenges and supporting the advancement of future projects and investment decisions in Finland, and the integration of the value chain for hydrogen derivatives as clean ammonia.

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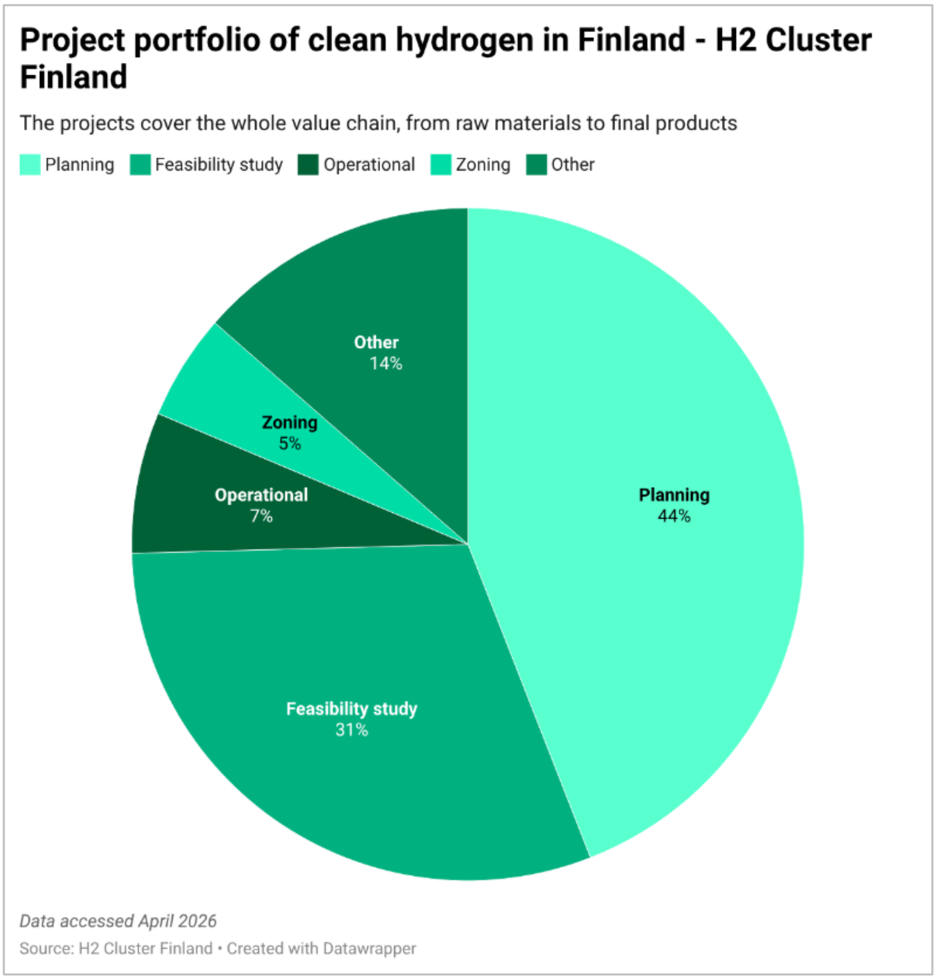

Figure 10. Project portfolio of clean hydrogen in Finland. Based on (Hydrogen Cluster Finland, 2026).

- ### Ammonia synthesis

Ammonia synthesis requires hydrogen and nitrogen. First, nitrogen is obtained by separating the N_2 stream from argon, oxygen, and moisture by applying different technologies, for instance: Pressure Swing-Adsorption (PSA), Air Separation Unit (ASU) or Membrane systems depending on the and specific characteristics of the project (Miltrup, 2025). Nowadays, ASU is the preferred technology due the high efficiency and nitrogen purity (Fichtner, 2025). On the other hand, for decentralised small-scale plants, technologies as the PSA or membrane separation are recommended. PSA is suitable for small-scale applications due to its compact and robust design with limited maintenance requirements in nitrogen production (Miltrup, 2025).

Second, regarding ammonia synthesis, the Haber-Bosch reaction is the primary industrial method to date (Fichtner, 2025). The Haber-Bosch is an exothermic reaction of nitrogen and hydrogen, as shown in the following equation:

$$N_2(g) + 3H_2(g) \rightleftarrows 2NH_3(g)$$

To achieve practical conversion rates, industrial ammonia synthesis requires high pressure, elevated temperature, and the use of a catalyst, for example, in the presence of an iron-based catalyst to accelerate the reaction (350-400 C and 100-400 bar) (Alho et al., 2024; Fichtner, 2025; Rouwenhorst, 2026). Since the reaction is controlled by thermodynamic equilibrium, complete conversion of the reactants in a single pass through the reactor is not possible. As a result, only a fraction of the nitrogen is converted to ammonia in each pass (Fichtner, 2025). After the reaction, the ammonia is separated from the remaining nitrogen and hydrogen by cooling the gas mixture to condense the ammonia, followed by a series of separation stages at different pressures. The unreacted gases are recirculated to the process, enabling high overall conversion through repeated recirculation. The final ammonia is sent to storage or further processing, while continuous recirculation ensures efficient use of raw materials (Fichtner, 2025).

In small-scale decentralised environments, ammonia production is typically located in modular, containerized systems that can be customized to meet consumer needs. These are miniaturized Haber-Bosch reactors with a relatively high level of automation, which can be produced and installed much faster and more easily than conventional centralised configurations (Kirk et al., 2024; Miltrup, 2025). One of the requirements for decentralised clean ammonia production settings is to provide the system with the necessary flexibility to respond quickly to changes in production and resource availability (Kirk et al., 2024). One of the main challenges of decentralised systems is the increased heat loss resulting from the lower surface area-to-volume ratio characteristic of smaller reactors. Consequently, a significant portion of the heat of reaction is dissipated into the environment instead of being efficiently utilized within the process (Miltrup, 2025).

- **Potential use of by-products:**

By-products from hydrogen-to-ammonia products are mainly oxygen and waste heat. Process design for decentralised small-scale plants can consider alternative solutions for the use of these by-products. For example, oxygen, of which approximately 8 kg are generated for every kilogram of clean hydrogen produced, can be harnessed instead of being released into the atmosphere (Miltrup, 2025). Potential applications include its use in wastewater treatment processes or to enhance biological activity in surface water systems, thereby improving overall resource efficiency and generating additional environmental benefits (Miltrup, 2025).

As regards waste heat, this can be recovered from integrated hydrogen-to-ammonia production systems and reused for process preheating or for space heating/cooling (Miltrup, 2025). However, these by-products valorisation alternatives can increase investment costs and add complexity to the system.

- **Transportation, compression, and storage:**

Ammonia has a long history of large-scale industrial use, resulting in well-established and mature systems for its transport, storage, and distribution (Bonnet-Cantalloube et al., 2023). In Europe there are around 30 ammonia terminals, and about 150 ports with ammonia terminals worldwide (Bonnet-Cantalloube et al., 2023).

Although normally a gas, it is easily liquefied through refrigeration or moderate pressurization, allowing for efficient handling as a liquid. This property favours its widespread use in transportation chains and provides a solid foundation for expanding the use of clean ammonia. Transportation methods vary depending on distance, volume, and location (Fichtner, 2025). Maritime transport is the primary option for international and long-distance shipments, supported by specialized ammonia tankers and port infrastructure. Barges operate on inland waterways and coastal routes, while pipelines offer a continuous and reliable solution for large overland volumes. Trucks and rail are used for short and medium distances, offering flexibility for small deliveries, although they present challenges in terms of cost-effectiveness due to empty return trips (Bonnet-Cantalloube et al., 2023; Fichtner, 2025).

Storage plays a vital role throughout the ammonia value chain, balancing production, and demand. Large, fixed storage tanks are used at production plants and import/export terminals, while end users maintain on-site storage to ensure operational continuity. Fully refrigerated storage systems are most common for large-scale applications, as they reduce material requirements and overall capital costs, despite higher energy consumption.

Decentralised small-scale configurations present challenges for ammonia storage related to limited space, reduced volumes, limited on-site infrastructure, and fluctuating renewable energy supply. Pressurized storage is preferred for small-scale, modular applications due to its simpler and safer operation (Fichtner, 2025; Miltrup, 2025) .

2.2.3 Downstream

- **Potential applications of clean ammonia (established and emerging markets):**

Ammonia is the second most produced synthetic chemical globally, after sulfuric acid. Likewise, ammonia is the precursor of chemical products, and it is widely used in industrial sectors to produce textiles, pharmaceuticals, refrigeration, air treatment, among other uses (Fichtner, 2025; Rouwenhorst, 2026). The relevant of ammonia calls for urgent actions in terms of greening today's ammonia production and presents a significant opportunity for decarbonisation of hard-to-abate sectors (Guidehouse Netherlands B.V., 2023; Hydrogen Europe, 2023).

Currently, ammonia represents the second largest demand for pure hydrogen, where about 80% utilized in the production of nitrogen fertilizers (Guidehouse Netherlands B.V., 2023; IRENA & AEA, 2022). In 2020, the global demand for ammonia exceeded 180 million tonnes (IRENA & AEA, 2022). Here, nitrogen fertilizers are recognized worldwide as a fundamental input for food production, playing a crucial role in supporting agricultural productivity and improving crop yields (Fichtner, 2025; Rouwenhorst, 2026). In terms of the application of nitrogen fertilizer, it differs according to the location and the type of crop. According to IRENA & AEA (2022), the nitrogen fertilizer application in Europe by product correspond around 40 % to nitrates, 23 % to urea, 13 % to urea ammonium nitrate, 11 % to other products, 10 % to nitrogen – phosphorus – potassium and 3 % to monoammonium phosphate (Figure 11). In 2019, European imports of N-fertilizers reached about 3.9 million tonnes, in comparison with 2,2 million tonnes of phosphorus pentoxide and 1.8 million tonnes of potassium oxide fertilizers (Fertilizers Europe, 2022).

Transiting towards clean ammonia fertilizer does not imply major innovations in terms of transport or distribution, or from the application point of view (Sandalow et al., 2022). However, decarbonising the entire ammonia value chain in fertilizer production requires considerable efforts, including substantial investment (IRENA & AEA, 2022; Rouwenhorst, 2026) This transition also carries the risk of increased production costs, which could raise fertilizer prices for farmers. Therefore, decarbonising the fertilizer industry demands robust and well-designed regulatory instruments, as well as incentive mechanisms that support the transition while limiting negative impacts on food prices (Rouwenhorst, 2026). Furthermore, it is necessary to develop the required skills within the food and agriculture sector and foster the integration of the value chain and its stakeholders, from large players to small and medium-sized enterprises, cooperatives, associations, and other related social structures such as ecosystems (Pinilla-De La Cruz, 2025; Pinilla-de La Cruz, 2026).

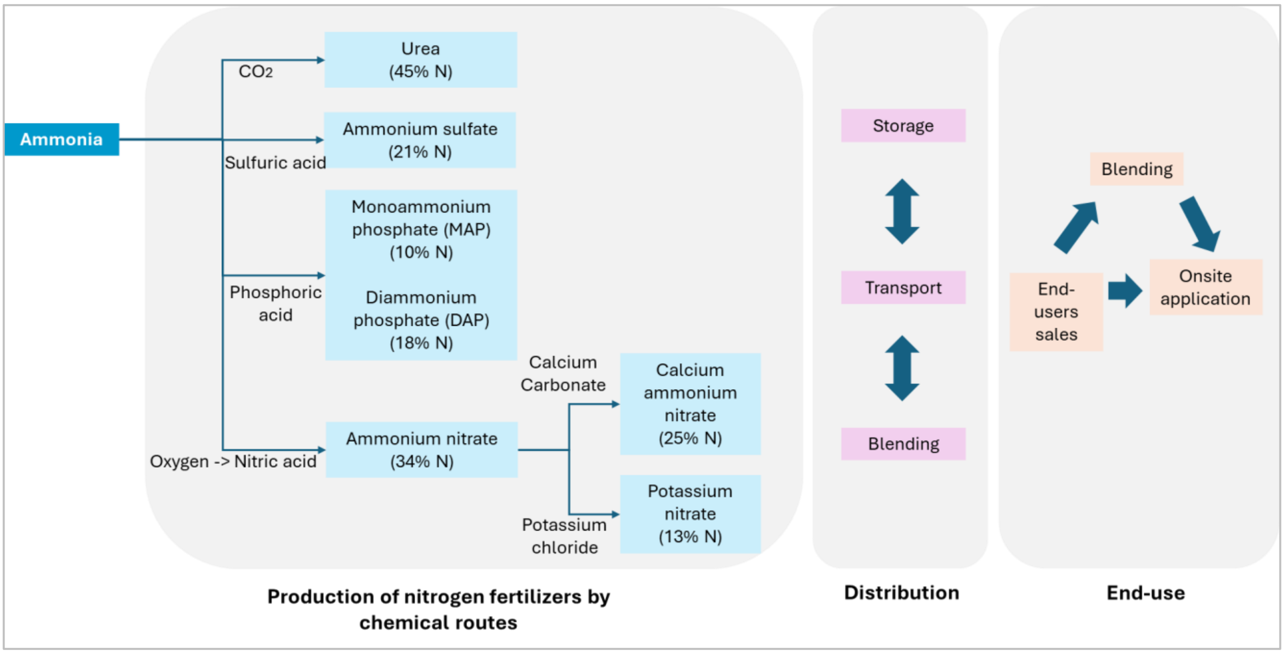

Figure 11. Production of key nitrogen fertilizers. Based on Agora Industry (2025), Alho et al., (2024), and Sandalow et al. (2022).

In regions with access to affordable electricity and large-scale agricultural activity, there is a growing trend toward decentralised fertilizer production (Agora Industry, 2025; Alho et al., 2024). This approach promotes the decarbonisation of the sector by distributing production closer to end users, thereby reducing transportation and distribution needs, dependence on imports, and exposure to global market volatility (Agora Industry, 2025). Furthermore, decentralised production can generate greater regional benefits by strengthening local capacities, fostering technological development, and creating new opportunities for smart specialization among small and medium-sized enterprises (SMEs). Integration along the value chain facilitates knowledge transfer and enables smaller players to meet the operational and quality standards required by large industrial companies.

Given the high costs associated with transitioning to low-carbon fertilizer production, new business models are needed to support decentralised nitrogen fertilizer systems (Agora Industry, 2025). This shift is also expected to stimulate the emergence of new services related to the sector, creating opportunities for other market participants to offer solutions that improve integration, value creation, and value capture across the value chain. A key factor would be the modernization of the agricultural sector to ensure long-term efficiency and scalability. Achieving this transformation will require coordinated efforts among public institutions with clear vision and suitable incentives and funding instruments, academic organizations, and private companies across all segments of the fertilizer value chain (Rocque et al., 2024).

Among the initiatives for the decarbonisation of ammonia for fertilizer production are several international projects that provide reference information for national stakeholders interested in the opportunities offered by the clean ammonia industry. In 2023, a clean hydrogen plant for ammonia production in Norway began operations. This 24 MW electrolyser plant produces 10 tonnes of hydrogen per day with storage, and its annual ammonia production is 20 000 tonnes (Yara International, 2023). According to Yara International, the use of low-carbon fertilizers in agriculture, in the quantities offered by this plant, has the potential to contribute significantly to Norway's food system. It is estimated that around 15% of the country's agricultural land could be cultivated with these fertilizers, representing between 60% and 65% of the national cereal production. Consequently, the food produced with these fertilizers could feed nearly one million people annually, highlighting the significant role they can play in supporting sustainable farming practices and food security (Yara International, 2023).

Another example of remarkable projects in low-carbon ammonia production for fertilizers is the Puertollano plant in Spain run by Fertiberia and Iberdrola (Iberdrola, 2022). This project is a large-scale industrial initiative focused on decarbonising fertilizer production through the integration of green hydrogen. Hydrogen is produced on-site via water electrolysis powered by renewable energy. The plant utilizes a 20 MW PEM system with a production capacity of approximately 360 kg of hydrogen per hour. Electricity for the electrolyser is supplied by a photovoltaic plant and supplemented by a battery energy storage system, ensuring stable operation and complete electrification of the process with zero direct emissions. The project is supported by the Puertollano II photovoltaic solar plant, with an installed capacity of 100 MW. This plant incorporates advanced technologies such as bifacial solar panels and high-efficiency inverters to maximize energy generation. Furthermore, a 5 MW lithium-ion battery system with a storage capacity of 20 MW hours enhances operational flexibility and optimizes energy management (Iberdrola, 2022).

In addition, several initiatives are underway at the global scale: the Australian Renewable Energy Hub is expected to reach a production capacity of approximately 5 850 000 tonnes of ammonia per year, while the NEOM plant in Saudi Arabia is designed for a capacity of around 650 000 tonnes per year. Similarly, the Oman Green Energy project aims to achieve an annual production of approximately 6 500 000 tonnes of ammonia (World Bank and ESMAP, 2025).

In Finland, one of the projects in planning phase is Naantali plant by Green North Energy. This project is planned to produce clean ammonia with an electrolyser capacity of 280 MW. The investment value for this project is around 600 million EUR (Green North Energy, 2026a).

In terms of new markets for clean ammonia emerging as a promising and cost-effective alternative to conventional ship fuels, power generation and energy storage, and heavy-duty road transport (Fertilizers Europe, 2022; IRENA & AEA, 2022; Sosa et al., 2025) (Figure 12). Furthermore, during the transition from fossil fuels to low-carbon fuels, clean ammonia could be blended with conventional fuels (American Chemical Society, 2021). Indeed, clean ammonia as a marine fuel is gaining attention due to the current regulations on the decarbonisation of the shipping sector, where Finland with long tradition and extensive know-how in this field could reach an important position in the market development of clean ammonia (Green North Energy, 2026b; Miltrup, 2025; Sandalow et al., 2022).

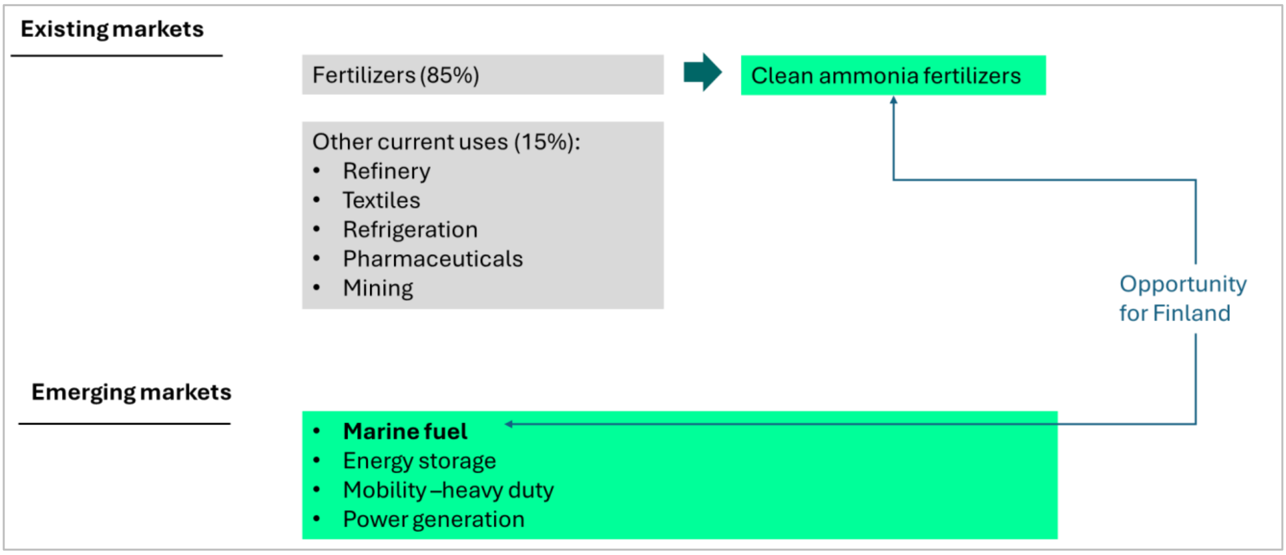

Figure 12. Ammonia existing and emerging markets. Based on Fertilizers Europe (2022), Green North Energy (2026b), IRENA & AEA (2022), and Sandalow et al. (2022).

3 Value chain technical and economic analysis

The techno-economic analysis of the value chain in this case encompassed the hydrogen production to the production and storage of ammonia. The calculations presented below are market value estimates based on reports, studies, academic articles, technical fact sheets and websites of equipment suppliers and market players. The results of this analysis serve as a reference, although they are not exhaustive, providing information for regional stakeholders regarding the scale and potential considerations when undertaking small-scale clean ammonia initiatives. It is expected that future studies will refine and narrow the scope of the approach presented here.

3.1 System description: small-scale clean ammonia production

In line with the current economic context for hydrogen projects in Finland, the most plausible option would be to opt for a small-scale design that reduces investment risks and allows testing the setup in the region. Indeed, this plant configuration has been the result of discussions within the project team and experts in the field, in which it was concluded that the first step for a region with no experience in the matter and with the challenge of integrating the value chain would be the implementation of a pilot project of the smallest possible dimensions that can prioritize learning about the industry, working on technical, logistical and commercial barriers, and the development of synergies between regional actors so that the results can provide relevant information for more ambitious projects with realistic prospects and less risk.

This setup consists of a 1 MW PEM-based system, which would produce approximately 425 tonnes of clean ammonia per year including: hydrogen production and storage, nitrogen production unit (Pressure Swing Adsorption - PSA), and ammonia production loop and storage. The following is a description of the system's composition (Figure 13).

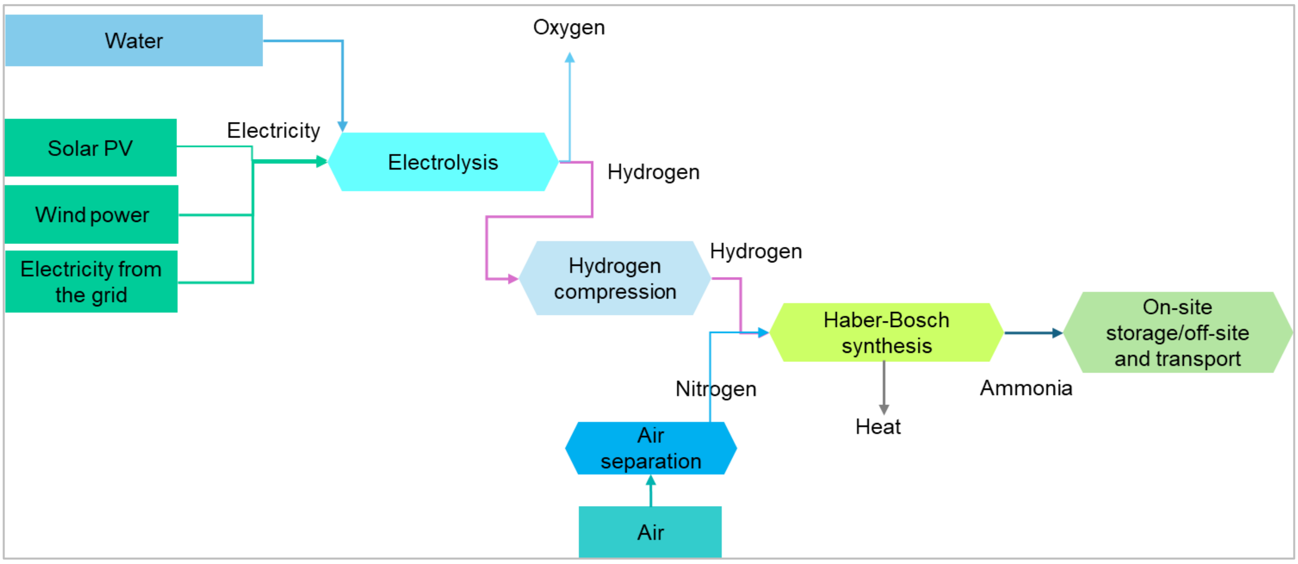

Figure 13.Schematic of hydrogen to ammonia production

3.2 Techno-economic analysis

The techno-economic analysis in this case study included estimating capital expenditures (CAPEX) and operating expenditures (OPEX) and roughly calculating the levelized cost of ammonia (LCOA) for a general pilot plant configuration with a 1 MW electrolyser capacity and 425 tonnes of ammonia per year. The system scope considered two subsystems: the hydrogen production subsystem and the ammonia loop and storage subsystem. For the calculation of the LCOA, the following equation based on discount cash flow was used for the analysis of this case:

$$\mathrm{LCOA} = \frac{\mathrm{CAPEX}_0 + \sum_{t=1}^{n} \frac{\mathrm{OPEX}_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_t}{(1+i)^t}}$$

Where:

$CAPEX$: capital expenditures or investment expenditures (EUR)

$OPEX$: operating expenses per year (EUR)

M: yearly production of ammonia per year (tonnes of NH_3)

n: economic lifetime in years

i: real interest rate (%) (here as Weighted Average Cost of Capital -WACC, representing full financing cost)
t: year of lifetime

This equation relates the present value costs including investment and operative costs with the present value of the ammonia production. For Capital expenditures (CAPEX), we consider all costs associated with the investments required to develop a hydrogen-to-ammonia production plant, including expenses for equipment, infrastructure, and land acquisition. This definition of CAPEX excludes costs related to transportation, downstream processing for end-use applications, and the energy supply used for hydrogen production (Agora Industry, 2025; European Hydrogen Observatory, 2024). On the other hand, operating expenses (OPEX) include labour costs, maintenance costs, utility consumption, and general and administrative expenses (Wu & Buyya, 2015).

3.2.1 CAPEX

To estimate the overall system capital expenditures, the investment costs of the hydrogen production subsystem were first assessed using cost references published by the IPCEI within the European Hydrogen Observatory, Agora Industry and relevant academic articles (Agora Industry, 2025; IPCEI Hydrogen, 2026; Terlouw et al., 2022; Wang et al., 2021). Assumptions for the hydrogen subsystem include: i) the cost of the stack includes the equipment, engineering, procurement, and installation; ii) the cost of the rest of the plant includes the equipment, engineering, procurement, and installation of the rectifier, the transformer directly connected to the rectifier, the gas/liquid separation system, the water feed system, and the gas purification system; iii) other service costs include the equipment, engineering, procurement, and installation of high-voltage transformers, water treatment equipment, refrigeration, hydrogen compression (if required by the system), the control system, and other services; iv) further CAPEX costs include land and utility fees, insurance, permits, feasibility studies, contingencies, and EPC management. The CAPEX for the hydrogen production subsystem will be 2 196 000 EUR, where:

- Stack cost: 494 000 EUR
- Balance of Plant (BoP): 567 000 EUR
- Other utilities: 608 000 EUR
- Other CAPEX: 527 000 EUR

Regarding the cost of the ammonia loop and storage subsystem is assumed that the production of one tonne of ammonia requires 177 kg of hydrogen. The CAPEX for the ammonia loop and storage subsystem, including the Pressure Swing Adsorption (PSA) unit reaches approximately 1 297 520 EUR (Agora Industry, 2025; Ammonia Energy Association, 2018; Rosbo et al., 2025; Wang et al., 2021), where:

- Ammonia loop cost and storage: 967 520 EUR
- Nitrogen production unit (PSA): 660 000 EUR

3.2.2 OPEX

The OPEX for this configuration can be explained in terms of the system's operational costs, which include the following items:

- System electrolyser electricity consumption
- Water consumption
- Fixed PEM and nitrogen production unit OPEX
- Stack replacement
- Electricity consumption in the nitrogen production unit
- Hydrogen compression
- Electricity consumption in the ammonia loop and storage
- Catalyst replacement (annualized)
- Electricity consumption in the ammonia compression

For OPEX calculation, electricity cost is applied as the reference price of Power Purchase Agreement (PPA) price wind/solar PV of 0,473 EUR/kWh in Finland according to KYOS (2025). Reason to apply PPA to this analysis is the need to provide reliability in the supply of electricity in the long-term to produce hydrogen-to-ammonia, taking into consideration the high variability and uncertainty of weather-dependent energy sources as wind and solar PV power (IRENA -International renewable energy agency, 2018). As a result of this analysis, total OPEX per year reached 372 453 EUR for this plant configuration.

3.2.3 Levelized cost of ammonia

The levelized cost of ammonia (LCOA) was estimated assuming a 20-year system lifespan with an ammonia production of 425 t/year and 1 MW electrolyser capacity. The findings indicates that LCOA remain above current market prices of grey and green ammonia (described in chapter 2.11), ranged in this particular case of analysis from 1536 to 1977 EUR/ tonne of ammonia (Figure 14). This is primarily due to the small scale of the proposed configuration, which limits economies of scale and negatively impacts the overall economic performance of the system. It is important to mention that the current estimate does not fully account for the logistical aspects of the value chain. It assumes an integrated production configuration and therefore does not consider potential additional costs related to the value chain integration. Consequently, the actual costs associated with implementing a similar configuration may vary depending on local conditions, infrastructure availability, and the value chain specificities.

Regarding the real interest rate for the LCOA calculation, the Weighted Average Cost of Capital (WACC) was applied. This metric is preferred because it reflects both the cost of debt (interest rate) and the expected return on equity, thus providing a comprehensive representation of the total economic cost of capital investment. A base WACC of 7% was used, which is consistent with a new project scenario without political support, reflecting moderate investment risk. Furthermore, a range of WACC scenarios were considered to provide a sensitivity analysis for various levels of risk (Figure 14). A low-risk scenario (5%) represents projects that benefit from favourable financing conditions, such as political support or secure purchase agreements. Conversely, higher-risk scenarios (9–12%) reflect uncertainties related to demand, purchase agreements, price volatility, and regulatory conditions. The impact of these different financing assumptions in terms of WACC on the Levelized Cost of Ammonia (LCOA) is illustrated in the sensitivity analysis presented in Figure 14. This analysis could serve an initial input for planning next steps in building the regional vision for the development of the hydrogen economy. Regional actors need to consider the implications of greenfield projects versus brownfield projects. Significant efforts and higher cost are connected to the necessary steps test the value chain integration in the first place and gain enough experience to overcome the learning curve with a small configuration to de-risk further initiatives with bigger scope and scale.

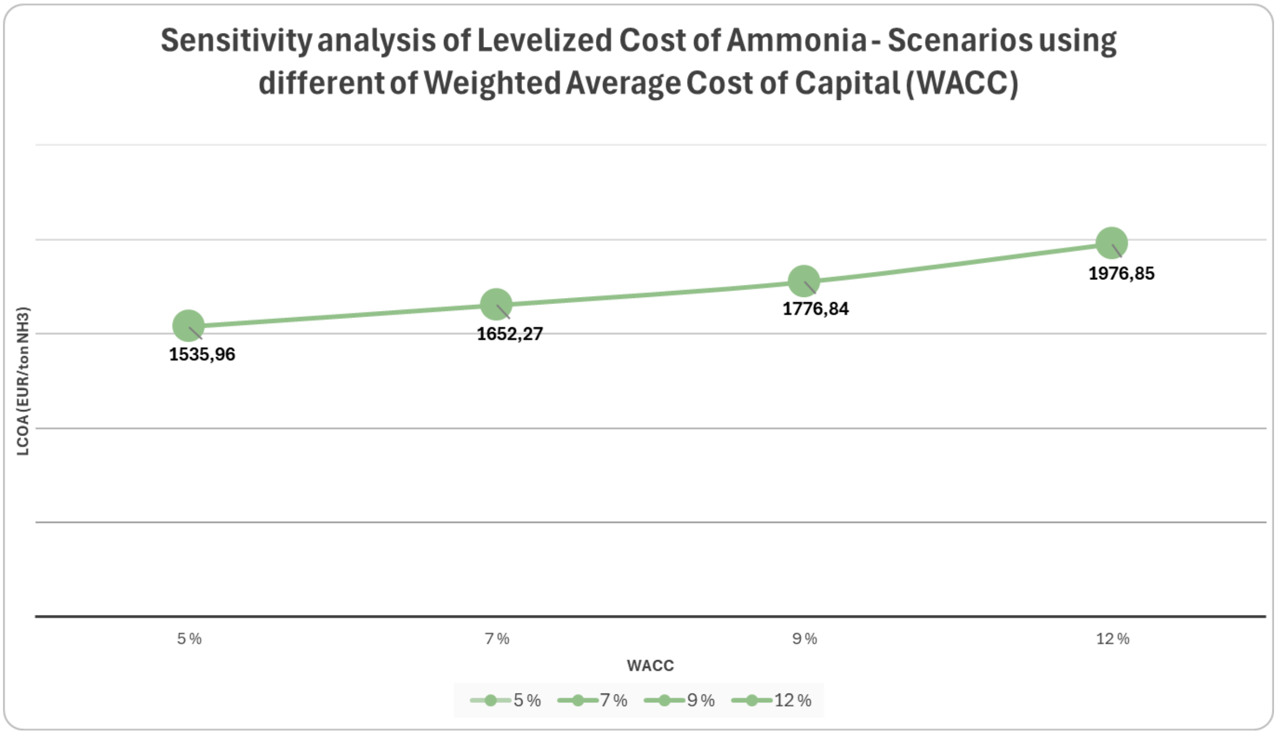

Figure 14. Sensitivity analysis of Levelized Cost of Ammonia - scenarios of different Weighted Average Cost of Capital

3.2.4 Pathways to move forward

As shown in the previous techno-economic analysis, the implementation of newly developed clean ammonia projects in decentralised and small-scale configurations faces significant economic challenges, especially compared to the established supply of conventional (grey) ammonia. To address this competitiveness gap, targeted policy interventions are essential. In this context, governments can facilitate the development of long-term purchase agreements with predetermined pricing structures in key sectors such as food production and agriculture. Such mechanisms would help reduce producers' financial uncertainty while fostering greater market stability (World Bank and ESMAP, 2025).

From a financial perspective, funding organisations can play a critical role by offering favourable credit terms and implementing risk-sharing mechanisms that incentivise private investment in clean ammonia projects (World Bank and ESMAP, 2025). These measures are particularly important for mitigating the perceived risks associated with emerging technologies and markets. Furthermore, for applications in the fertilizer sector, governments and relevant organizations could promote the development of certification schemes and ecolabels to differentiate clean fertilizers from conventional alternatives (World Bank and ESMAP, 2025). This would improve market transparency, raise consumer awareness, and create added value for low-carbon products.

In the fertilizer sector, particularly in connection with food and agricultural systems, there is a growing need to support the transition from urea-based fertilizers to alternative nitrogen carriers, such as ammonium nitrate and ammonium phosphate, which are more compatible with low-carbon production pathways (World Bank and ESMAP, 2025). However, these cleaner fertilizer options are currently associated with higher costs. Therefore, a combination of financial incentives (e.g., subsidies or tax breaks) and non-financial support measures will be essential to encourage their adoption among farmers (World Bank and ESMAP, 2025).

At the same time, it is crucial to promote awareness and knowledge transfer among farmers, cooperatives, and rural communities to improve understanding of the benefits of cleaner fertilizers. Strengthening stakeholder engagement will be key to generating social acceptance and facilitating the transition to more sustainable agricultural practices (World Bank and ESMAP, 2025).

4 Conclusions

The present report shows that South Ostrobothnia region possesses several strategic advantages for developing a clean hydrogen value chain, particularly one focused on ammonia production in decentralised small-scale configurations. These advantages include abundant and rapidly expanding renewable electricity capacity, robust agricultural and agri-food sectors, and growing demand for low-carbon fertilizers and marine fuels. Together, these factors provide a solid foundation for integrating clean hydrogen solutions into the regional economy.

Decentralised small-scale ammonia production could have direct relevance for agriculture, national fertilizer security, and emerging marine fuel markets, and aligns well with South Ostrobothnia's industrial structure and long-term development opportunities. Furthermore, ammonia offers flexibility both as an end-product and as a potential hydrogen carrier, increasing its strategic importance within Finland's hydrogen ecosystem. It could also open new opportunities to create and capture value through the application of novel business models involving local and regional stakeholders.

The techno-economic analysis highlights that small-scale clean ammonia production is not yet competitive with fossil fuel-based alternatives under current market conditions. However, the results also demonstrate the need to capitalize on learning curves by implementing small-scale pilot projects as initial steps. These projects can play a crucial role in developing regional expertise, testing technologies, and logistics, strengthening collaboration among stakeholders, and reducing uncertainty for future investments.

In general, the findings suggest that a phased, learning-oriented approach is the most appropriate path for South Ostrobothnia. Initial small-scale projects can facilitate capacity building, value chain integration, skills development, and institutional learning, while laying the groundwork for larger industrial investments in the future. To harness this potential, coordinated actions would be needed among public authorities, energy developers, agricultural stakeholders, technology providers, and research organizations. Clear policy signals, targeted financing instruments, long-term power purchase agreements, and supportive regulatory frameworks will be essential to translating the region's structural advantages into a viable and competitive clean hydrogen value chain.

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