Breaking the green hydrogen deadlock? Contextual factors for hydrogen-based fuels in Nordic ports

Citation for the original published paper (version of record):
Corcoran, C., Hansson, J., Wårell, L. et al (2026). Breaking the green hydrogen deadlock? Contextual factors for hydrogen-based fuels in Nordic ports. Energy Research and Social Science, 138. http://dx.doi.org/10.1016/j.erss.2026.104848

Energy Research & Social Science 138 (2026) 104848

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Breaking the green hydrogen deadlock? Contextual factors for hydrogen-based fuels in Nordic ports

Cary Kincaid Corcoran [a,*], Julia Hansson [b,c], Linda Wårell [d], David Cook [e], Brynhildur Davíðsdóttir [f], Lára Jóhannsdóttir [g], Cecilia Wallmark [h], Joakim Lundgren [h,i]

[a] Environment and Natural Resources, Faculty of Economics, University of Iceland, Gimli, Sæmundargötu 2, 102, Reykjavík, Iceland
[b] Sustainable Society, IVL Swedish Environmental Research Institute, Aschebergsgatan 44, 411 33, Gothenburg, Sweden
[c] Department of Mechanics and Maritime studies, Division Transport, Energy and Environment, Chalmers University of Technology, Campus Johanneberg, 412 96, Gothenburg, Sweden
[d] Division of Social Sciences, Economics Unit, Luleå University of Technology, 971 87, Luleå, Sweden
[e] Environment and Natural Resources, Faculty of Environment and Life Sciences, University of Iceland, Gimli, Sæmundargötu 2, 102, Reykjavík, Iceland
[f] Environment and Natural Resources, Faculty of Environment and Life Sciences and Faculty of Economics, University of Iceland, Sæmundargötu 2, 102, Reykjavík, Iceland
[g] Environment and Natural Resources, Faculty of Business Administration, University of Iceland, Gimli, Sæmundargötu 2, 102, Reykjavík, Iceland
[h] Division of Energy Science, Luleå University of Technology, 971 87, Luleå, Sweden
[i] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361, Laxenburg, Austria

ARTICLE INFO

Keywords:
Hydrogen
Ports
Development
Deployment
Drivers
Barriers
Stakeholders

ABSTRACT

To fulfil climate change commitments and transition towards net zero carbon economies, there is a need for Nordic nations to explore the development and deployment of alternative fuels. In this context, this inquiry presents the first comparative analysis of drivers for and barriers to implementing green hydrogen and hydrogen-based fuels (hydrogen, methanol, ammonia) within potential hydrogen hubs in Nordic ports. To support the development of hydrogen hubs to meet ambitious decarbonization targets for maritime shipping and relevant industry, this study focuses on five case studies from Sweden and Iceland. 64 semi-structured interviews with diverse stakeholders are used to examine the potential for ports to become hydrogen hubs. This is done by exploring the relative strength of drivers and barriers related to different phases of hydrogen hub development and the influential context-specific and necessary enabling factors. Key findings illustrate market opportunities, consumer demand, and environmental commitments as shared drivers for each case, while high costs, insufficient policy instruments, and limited energy resources and grid capacity emerge as shared barriers. The frequently dualistic nature of these factors underscores the need for policy frameworks to bridge the gap between current limitations and future potential. The main policy implications include a need for provision of funding for more Nordic pilot projects, increasing renewable electricity capacity, and implementing sufficient economic incentives to support hydrogen-based fuel upscaling and ensure cost-competitiveness in comparison with existing fossil fuel-based alternatives. This can help to encourage strategic investments in infrastructure and coordinated policy measures to unlock the potential of hydrogen hubs.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), global carbon neutrality needs to be reached by 2050 to fulfil the aims of the 2015 Paris Agreement [1]. Progress towards that goal has been slow to date. Global greenhouse gas emissions (GHG) reached their highest level yet in 2024, increasing by 2.3% from 2023 levels [2]. To close the emissions gap, i.e., the difference between current Nationally Determined Contribution (NDC) pledges and the fulfillment of the Paris Agreement's 1.5 degrees Celsius goal, immediate reductions in GHG emissions across all sectors is needed [3].

International marine shipping was responsible for around 1.4% of

* Corresponding author.
E-mail addresses: ckc2@hi.is (C.K. Corcoran), julia.hansson@ivl.se (J. Hansson), Linda.Warell@ltu.se (L. Wårell), dac@hi.is (D. Cook), bdavids@hi.is (B. Davíðsdóttir), laraj@hi.is (L. Jóhannsdóttir), cecilia.wallmark@ltu.se (C. Wallmark), joakim@ltu.se (J. Lundgren).

https://doi.org/10.1016/j.erss.2026.104848
Received 28 January 2026; Received in revised form 2 July 2026; Accepted 8 July 2026
Available online 16 July 2026

global GHG emissions in 2024 [4]. In July 2023, the International Maritime Organization (IMO) revised its GHG emissions strategy for ships, which aims to reduce GHG emissions from international shipping by 20% by 2030 compared to 2008 levels (striving for 30%) and by 70% (striving for 80%) in 2040 [5]. Net-zero emissions should be achieved by close to 2050. Additionally, the European Union (EU) aims to reduce GHG emissions from transportation by 90% by 2050, including marine transport [6]. Such ambitions are pushing decarbonization in the maritime industry [7,8].

Green hydrogen, which is hydrogen produced from renewable electricity sources and water [9], and green hydrogen-based energy carriers (including carbon or nitrogen) are often identified as key future technologies for sustainable energy and transport systems in hard-to-abate sectors such as industrial- and heavy-duty transport systems including shipping [7,10,11]. The EU, for example, foresees green hydrogen as a key element in reaching carbon neutrality by 2050 [12]. The Nordic countries have expressed similar interest and have developed national roadmaps and strategies related to hydrogen or similar initiatives [13–17]. However, the current global supply and uptake of green hydrogen and derived fuels (in this paper jointly called hydrogen-based fuels) is limited [18,19]. This has been described by IRENA as the "green hydrogen deadlock" [20 pg. 84]. The overall barriers for the production and uptake of green hydrogen include high production cost and lack of technological maturity, lack of competitiveness with fossil fuels or fossil hydrogen, lack of regulatory frameworks and economic incentives, lack of infrastructure, uncertain demand, and lack of take-off agreements [8,20,21]. In particular, [8] includes a thorough literature review of drivers and barriers identified by different studies for hydrogen-based fuel development and deployment.

Ports can play a key role in influencing increased supply and demand of green hydrogen-based energy carriers, such as hydrogen, ammonia, or e-methanol through sector coupling or energy system integration [9,22,23]. Ports can shape the energy value chain through their multiple functions (such as regulator or operator) and their role as nodes in transportation networks; consequently, innovations implemented in ports can diffuse to both sea and hinterland transport [22,24]. They can further advance the energy transition by functioning as hydrogen hubs [22]. A hydrogen hub is a geographically clustered network that is involved in the integrated production and offtake of hydrogen and hydrogen-based fuels [9,25]. A hydrogen hub located within a port may produce hydrogen-based fuels for maritime offtakers, as well as industrial uses [9,25,26]. Furthermore, some hydrogen-based fuels require carbon dioxide (CO2) as an input, meaning hydrogen hubs can reduce emissions upstream through sector coupling [26].

Hydrogen hubs are situated within specific local geographic regions, yet exert broad influence on regional, national and international scales [24,25]. The development of hydrogen hubs entails unique technological, social, economic, and political challenges at multiple levels (local, regional, national, international) and stages. Therefore, its drivers and barriers can be considered within a socio-technical perspective [23]. Much of the existing research reviews the factors influencing the energy transition within ports [22–24,27–34], however there is less focus on hydrogen hubs [8,9], and a gap analyzing the drivers for and barriers to establishing hydrogen hubs at different developmental stages. This paper will use the five development stages outlined in Fig. S1 in the Appendix, including conceptual hub, planned hub, initiated hub, early hub, and established hub in its assessment. It should be noted that due to the green hydrogen deadlock, many hubs have struggled to advance from the conceptual and planned development phases [8,20,35]. In this vein, there is thus also a need for studies assessing context-specific opportunities and challenges faced by ports linked to the transition to hydrogen-based fuels [24,30,31] to understand the potential role of ports and port areas as hydrogen hub, research which could help transform descriptive visions and conceptual hubs (i.e., ports could be hubs) into a predictive, actionable roadmaps for their real-world transition into planned and initiated phases.

The Nordic nations are an ideal lens through which such an analysis can be conducted, given they have some of the highest ambitions for decarbonization, considerable availability of low-carbon electricity, and relatively low electricity prices [36], as well as currently possessing the largest number of maritime technology demonstrations of alternatives fuels in the world and a widespread interest in the development of hydrogen hubs [19,37]. Chen et al. [32] conclude that the readiness of ports for hydrogen-based fuels globally is still at an early stage, and the formation of hydrogen supply chains needs to be accelerated. Norway is the only Nordic country discussed in that study, although other Nordic countries are interesting from a hydrogen perspective. For example, in Sweden, many of the hydrogen initiatives for cluster/valleys are linked to or include port areas [37,38] and in Iceland, where marine applications, such as shipping and fishing, are responsible for around one-third of fossil fuel use, the focus inevitably is on port areas [16].

Although there has been much talk of potential promise and a variety of studies on technological, infrastructure, bunkering, land availability, and regulatory constraints worldwide [33,39–41], limited research exists that directly compares the hydrogen development conditions linked to different ports in the Nordic countries a gap that will be explored in this paper. Furthermore, combined focus on hydrogen hubs and their development stages constitutes a contribution of this paper and begins to address a previously underexplored gap in the literature. The aim of this study is thus to examine the relative strength of drivers and barriers relating to the implementation of hydrogen hubs (focusing on the fuels hydrogen, methanol, and ammonia) in five ports in Iceland and Sweden, and to discuss the contextual factors of hub development and enabling conditions. To address these aims, this paper will answer these three research questions.

1. What is the relative strength of the drivers and barriers for hydrogen hubs across different cases?
2. What context-specific factors influence the drivers and barriers for each case?
3. What are the enabling factors for hydrogen hubs and how do they compare for each case?

Understanding the relative strength of the drivers behind the initiatives in the included cases and the relative strength of the barriers hindering their realization may have important implications for the successful development of hydrogen hubs in port areas across the Nordic countries and elsewhere, potentially unlocking the green hydrogen deadlock [8]. This paper makes a novel contribution by providing a comparative assessment of the relative strength of drivers and barriers to hydrogen hub development using empirical data from five cases across two Nordic countries with varying contextual factors, while also focusing specifically on hydrogen hubs rather than ports in general. Thus, the paper, represents the first comparative stakeholder-centric study on hydrogen hubs in the Nordic region. Insights from such context-specific comparisons can potentially support the implementation of hydrogen-based fuels in other hydrogen hubs and port areas as well as more tailored and effective policymaking. In so doing, this inquiry can support the realization of hydrogen hubs in the Nordics in the short-term to meet the long-term GHG emissions reduction targets for shipping set by the IMO, EU, and national governments as well as similar decarbonization targets for relevant industry.

In comparison to the Icelandic study of the similar cases [8], besides adding empirical data from two more hydrogen hub cases in another Nordic country the empirical insights from the ranking sessions are novel from and used exclusively in this assessment.

The paper is structured as follows. Section 2 describes the five case studies and the interview and workshop-based methodology. The results are presented in Section 3. Section 4 discusses the context-specific factors for the drivers and barriers of each case, including necessary enabling conditions for hydrogen hubs to overcome the identified green hydrogen deadlock and policy implications. Conclusions are outlined in

Section 5.

2. Methods

This work attends a local-regional context, first comparing research from different cases, then synthesizing commonalities for learning within the Nordic region, contributing to climate and energy research as outlined by [42]. The study centers around five potential hubs for hydrogen-based fuels linked to ports in the Nordic countries, two in Sweden and three in Iceland. The cases differ in terms of context-specific factors e.g., location, port activities, ship traffic, nearby industries, resource availability, and initiatives for hydrogen-based fuels (including fuel type). Drivers and barriers for the implementation of hydrogen-based fuels in each of the assessed cases were identified via the framework of Corcoran et al. [8] that is based on a literature review and interview results, applied to semi-structured interviews with stakeholders, which were followed by a ranking exercise to determine the perceived strength of specific barriers and drivers. For the Icelandic cases the same semi-structured interviews as in. [8] were used as base but extended with ranking workshops and the contextual perspective. The following subsections outline the approach, including case descriptions, stakeholder mapping and interviewee identification, design of interviews and ranking exercises, and data analysis.

2.1. Case descriptions

The three hubs in Iceland include Ísafjörður, Húsavík and Grundartangi, while the two Swedish hubs are the ports of Luleå and Gothenburg (Fig. 1). The town of Ísafjörður is situated in the north-west of Iceland. The port is the country's third largest port for cruise ship arrivals [43]. In addition to tourism, maritime-related economic activities include aquaculture, fishing, fish processing, and shipping [43,44]. A potential green ammonia plant, powered by renewable electricity, is being considered for Ísafjörður, located close to its harborside [8]. The Ísafjörður hub is categorized in the conceptual stage, according to Fig. S1 in the Appendix.

The town of Húsavík is on the northeast coast of Iceland with a fishing and shipping port that also caters to tourism [45], with activities by primarily whale watching ships and some cruise vessels [45]. Potential production of e-methanol, fueled by renewable electricity, has been under consideration for Bakki, an industrial district located just outside the town. This collaboration may involve Landsvirkjun, the National Power Company of Iceland, and the heavy industrial firm PCC Bakki Silicon, a ferrosilicon metal producer capable of supplying a carbon dioxide (CO2) feedstock [46]. The partnership is expected to be located within the Árbakki Eco-Industrial Park, which is designed to foster industrial symbioses that minimizes GHG emissions between operations on the premises [47]. While Húsavík is further in development than Ísafjörður, this hub location is immature and remains in the conceptual stage of hub development as outlined by Fig. S1 in the Appendix.

Grundartangi is an industrial district located in a fjord, Hvalfjörður, close to Iceland's capital city of Reykjavík and operated by Faxaflói Ports [48]. The hydrogen hub of Grundartangi is classed in the planned hub stage according to Fig. S1 in the Appendix. Grundartangi hosts the aluminum smelting company, Norðurál, and Elkem, which produces silicon metal and steel products [49]. The industries aim to contribute to circular economy practices through industrial symbiosis. Land in Grundartangi has been secured by QAIR who has plans to develop hydrogen and ammonia, powered by renewable electricity [50]. QAIR intends to bring 280 MW of green hydrogen and green ammonia production online in 2028, with the total planned capacity of the Grundartangi hub being 840 MW after completion of its third intended phase [51].

The hubs in Sweden include Gothenburg, on the west-coast, and Luleå, which is in the north of Sweden. The Port of Gothenburg, the largest port in Scandinavia, handling 20% of all Swedish foreign trade, is in the middle of the city of Gothenburg, the second largest Swedish city [52]. The port covers several industrial activities, including the refineries by Preem and St1 currently using fossil-based hydrogen, and constitutes the largest container port in the Nordic countries [53]. However, the ship traffic by roll-on/roll-off (RoRo) vessels, roll-on/roll-off with passengers (RoPax), product and oil tankers represent the larger shares in fuel terms [54]. The Gothenburg region represents a key bunkering area for ships (covering besides conventional fossil fuels and LNG also fossil-based methanol and biomass-based methane – LBG), and there is considerable fuel storage. There are several initiatives linked to green hydrogen-based energy carriers in the port, except for the hydrogen handling linked to the refineries, planned to be green in the future. This is exemplified by the hydrogen refueling station in the port area offering green hydrogen for heavy traffic [55] and the plan for a 4 MW and two ton per day hydrogen production facility in the port area initiated by the Energy company Statkraft but now run by the Norwegian hydrogen producer Hydrogen Solutions AS (HYDS), with public support approved via the Swedish national support system

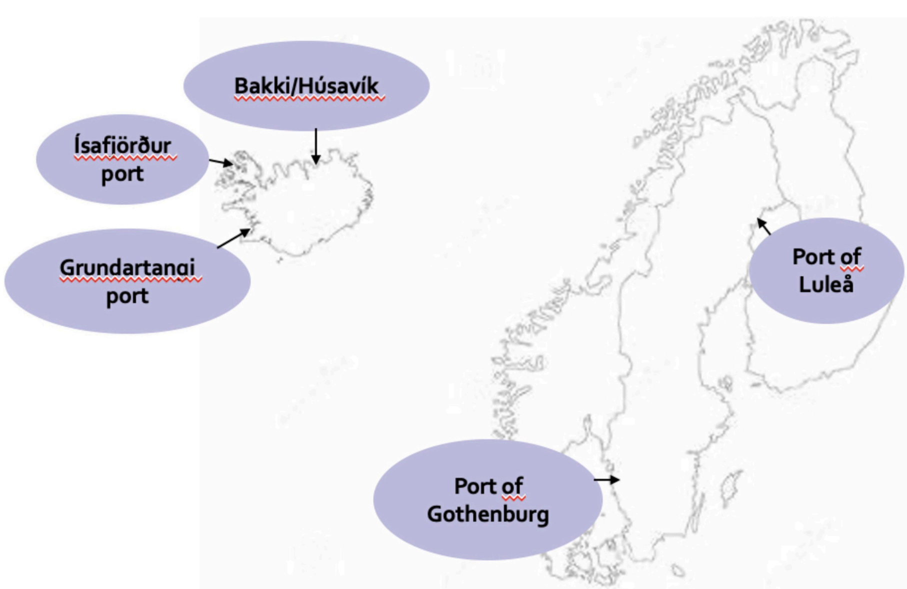

Fig. 1. Three hubs in Iceland and two hubs in Sweden are investigated in this paper.

"Klimatklivet" (off-taker not specified). The port of Gothenburg is also involved in the forming of several green shipping corridors, which are shipping routes running from one port to another on low carbon fuels [56]. The current focus is on ammonia and LBG, but hydrogen and e-methanol for selected ships have also been explored [57]. The hydrogen-based fuel hub in port of Gothenburg is defined to be in the initiated stage, according to Fig. S1 in the Appendix, as several hydrogen initiatives have passed the planning stage.

Luleå is located at the northern tip of the Gulf of Bothnia, which is the northernmost arm of the Baltic Sea. The port of Luleå is one of Sweden's largest and most important ports, especially for industrial purposes, supporting mining, steel production, and other heavy industries. The port of Luleå, is emerging as a strategic node in the country's green industrial transformation [58]. This development is driven by large-scale initiatives such as HYBRIT and Stegra, which aim to de-fossilize steel production using fossil-free hydrogen produced via electrolysis powered by renewable electricity [59] and biocarbon. These projects generate increasing demand for hydrogen-based fuel infrastructure, not only at the production sites but also in the surrounding logistics systems, including seaports. Other projects aimed at filling this demand are therefore under development, e.g. the Bothnia Link H2 aimed at producing e-methanol in the port of Luleå [60], and LKAB's plan for a circular industrial park where by-products from iron ore mining, such as phosphorus and rare-earth metals, will be extracted via circular and fossil-free processes. Green hydrogen and ammonia will be used to produce both mineral fertilizers and nitrate [61]. The port is currently expanding its capacity from about 8 Mton to 30 Mton of cargo to meet the demands of these green industrial initiatives. Due to its geographic proximity to industrial clusters, access to renewable electricity from hydropower and wind, and its role in bulk transport, the port of Luleå is well positioned to become an established hub for hydrogen use and distribution. The hydrogen hub in port of Luleå is defined to be in the initiated stage, according to Fig. S1 in the Appendix, mainly as a pilot-plant producing green hydrogen with electrolyzers already established.

Table 1 provides a summary of the core characteristics that underpin the potential for the five case studies to become hydrogen-based fuel hubs, and as such, constitute relevant ports for analysis in this inquiry. One central aspect not included in Table 1 is national and regional hydrogen ambitions and plans. Iceland aims to achieve climate neutrality by 2040 and to increase the share of renewable energy resources in the maritime industry to 10% by 2030. Iceland's Hydrogen and E-Fuels Roadmap [16] suggests potential economic instruments, including cash-flow subsidies or guarantees, income tax rebates, or CAPEX guarantees for green investments and outlines the need to create hydrogen hubs. The Swedish goal is zero net GHG gas emissions by 2045 at the latest and a reduction of GHG emissions from domestic transport including shipping by 70% by 2030 compared to 2010 [62]. There is no officially adopted hydrogen strategy in Sweden, but the Swedish Energy Agency proposed a national hydrogen strategy in 2021 [15]. However, there is a regional action plan for large-scale, green hydrogen production in Västra Götaland covering Gothenburg [63].

Another key aspect is the availability of renewable electricity. The Icelandic electricity grid is powered 99.9% from renewable energy [64] and in Sweden the renewable energy share is 69% and the fossil-free share 98% [65]. However, the potential additional supply of large-scale renewable electricity in both the Swedish and Icelandic cases depend on e.g., the regional availability due to transmission issues and realization of future electricity production. For example, in Gothenburg there are plans to increase local renewable electricity production, however, the electricity is currently more costly and limited than in the Luleå case.

Table 1
Summary of case-specific port and hydrogen-based fuel hub characteristics. Green shipping corridors refer to specific shipping routes run with renewable marine fuels.

	Ísafjörður, Iceland	Húsavík, Iceland	Grundartangi, Iceland	Luleå, Sweden	Gothenburg, Sweden
Size of nearby populations (municipality)	2800	2400	8500	80,000	613,000
Development stage (port and hub)	Established port, Conceptual hub	Established port, Conceptual hub	Established port, Planned hub	Established port, Initiated hub	Established port, Initiated hub
Main surrounding activities	Tourism and fish processing	Nearby Bakki is an industrial district with potential CO2 feedstock. Tourism and whale watching in the town of Húsavik	Aluminum smelting and a ferro silicon plant	Green steel production and other industrial activities	Refineries, energy port, terminals for containers, cars, and other rolling (RoRo) cargo. Bunkering for ships and fuel storage.
Ship traffic characteristics	Cruise ships, fishing, and shipping vessels.	Shipping, fishing, whalewatching, some cruise ships	Industrial and cargo ships	General cargo and bulk vessels	Several ship segments incl. RoRo, RoPax vessels, product and oil tankers, container vessels and cruise ships.
Main fuels in focus for the case	Ammonia	Methanol	Hydrogen, ammonia	Hydrogen, methanol, ammonia	Hydrogen, methanol, ammonia
Necessary resource availability	Constrained land and electricity access	Some access to renewable electricity and CO2	Some access to renewable electricity	Substantial access to affordable renewable electricity and bio-CO2. Limited power grid capacity to the port.	Certain access to renewable electricity and several bio-CO2 sources.
Main port specific hydrogen-related initiatives/plans	Potential production of ammonia to serve maritime industries operating in the port.	Potential production of e-methanol to serve maritime industries operating in the port.	QAIR aims to produce 280 MW green hydrogen and ammonia in 2028. Total planned capacity of Grundartangi hub: 840 MW of green hydrogen and ammonia	A pilot plant for fossil-free sponge-iron using green hydrogen (HYBRIT). SSAB invests in a new electric steel mill. Uniper plan to produce e-methanol for transport (Bothnia Link H2). LKAB plan for an industrial park for mineral fertilizers, using green hydrogen and ammonia.	Hydrogen refueling station for heavy-trucks available. Plan for 4 MW green hydrogen production. Methanol for ships available and ammonia bunkering is explored. Green shipping corridors initiatives. Refineries to increase share of renewable hydrogen-based fuels.

2.2. Design of semi-structured interview framework and ranking session

The research is based on 64 interviews across the five potential hub sites, which followed the same semi-structured interview format. This consisted of 10 core open-ended questions with additional sub-questions to help guide the interview as outlined by [8]. The interviews were performed in 2024; during February to September in the Icelandic cases, and this research was used in [8]. Interviews in the Gothenburg case were conducted September to December, and the Luleå case October to December. Semi-structured interviews were chosen as the main research method in this inquiry, as they are particularly useful for eliciting stakeholder perceptions and general attitudes about a particular problem [66].

A stakeholder mapping exercise was employed by the authors to identify the main stakeholders representing the different parts of the hydrogen value chain and supporting actors in the respective case studies. Thereafter, the study employed purposive sampling [67] to identify stakeholders representing the main categories identified during the mapping exercise: Public Governance, Energy Sector, Maritime Industry, Other Industry Actors, or the Research Sector. Stakeholders could be classified according to more than one category depending on their activity, and thus the total number of these exceeded the number of interviews. The stakeholders included in each case are listed in Tables S1-S3 in Appendix.

The number of interviews, interviewees, and participants in the ranking sessions, and the respective coverage across stakeholder categories is shown in Fig. 2. For the three Icelandic and the Luleå case, the identification of drivers, and barriers was conducted in the aftermath of the interviews, whereas for Gothenburg, it was done as part of the interviews. For the Icelandic cases, three separate ranking sessions with 23 participants were conducted after the 32 interviews to determine the strength of the identified drivers and barriers. The ranking sessions are novel from [8] and used exclusively in this research. All five case studies used the same scoring system of 1–3 points, with 1 corresponding to a factor not constituting any obstacle or being very minor/insignificant, 2 implying that the factor is important (i.e., considered a significant barrier/driver), and 3 corresponding to the factor being considered as a very challenging barrier or very important driver. The ranking exercise utilized the categorization of 27 drivers and 31 barriers identified by Corcoran et al. [8], initially for the cases in Iceland, building on the work on drivers and barriers by Latapí el al. [60] for hydrogen fuel cells the Nordic region. The drivers and barriers are described in Tables S4 and S5 in Appendix.

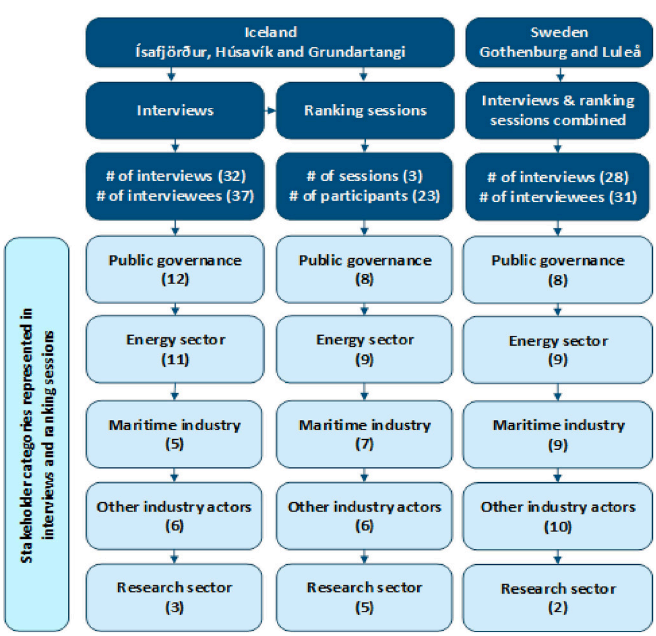

Fig. 2. Numbers of Interviewees, workshop participants, and stakeholder types.

The semi-structured interview framework can be found in the supplementary material of Corcoran et al. [8] and was applied to all five cases. The interviews conducted for Iceland were used in another paper [8], but the ranking sessions are novel to this study. The main aim of the interviews was to map drivers and barriers in each case. The themes included in the interview framework spanned the interest in projects and initiatives for hydrogen-based fuels, as well as the drivers, barriers, and enabling factors. While the theme identification was conducted through analysis of interviews, the results of the ranking sessions were provided by stakeholders from different hubs and are used to facilitate comparison across cases. The analysis in this paper is based primarily on the results of the ranking sessions, with comparatively less emphasis on the content of the interviews.

2.3. Extraction of information and data analysis

Interview information was organized by categories and subcategories of drivers and barriers, which are defined in Tables S4 and S5 in the Appendix. These codes originated from frameworks by Corcoran et al. [8] and Latapí et al. [68], with driver categories of 'Economic', 'Market', 'Infrastructure', 'Resources', 'Society', 'Organization', and 'Policies', and barrier categories of 'Economic', 'Technology', 'Infrastructure', 'Resources', 'Society', 'Organization', and 'Policies'. This categorization framework includes subcategories (Tables S4 and S5 in Appendix) and is concordant with other analyses on the drivers and barriers of decarbonization technologies [8,68,69]. Iterative meetings were held by the authors to ensure cohesion of data across the five case studies. The numerical ratings on the strength of the drivers and barriers were placed into a shared file to ensure ease of comparison with the other cases. The ratings were calculated as mean values in Excel based on all the individual scores provided by the stakeholders in each case. The context-specific factors and enabling factors were derived by integrating evidence from the interviews, ranking sessions, and existing literature on ports and hydrogen hubs. The categorization of hub development stages in Fig. S1 were inductively derived from the interview and ranking session results and informed by a synthesis of port and hub literature; these stages were then used to structure the analysis and discussion of context-specific and enabling factors.

3. Results

This chapter systematically describes and quantifies the relative strength of the categories of drivers (section 3.1) and barriers (3.2) described in the methods section. The numbers provided in the tables in Sections 3.1 and 3.2 are the mean ratings provided by the stakeholders in the five case studies. The enabling factors linked to overcoming the barriers and amplifying the drivers are then explored in the discussion Section 4.3. The meanings of each driver and barrier are described in Tables S4 and S5 in Appendix).

3.1. Drivers

Table 2 outlines the strength of the main economic and market-based drivers identified by stakeholders across the five cases. The tables include the mean rankings for the total stakeholder group in each case, and the highest ranked driver in each category is marked in yellow in the table. The number 3 corresponds to the factor being considered as a very important driver, 2 an important driver and 1 means the factor does not constitute a driver or is considered very minor.

The rankings in Table 2 indicate that the primary Economic drivers for both the Swedish and Icelandic cases are 'Cost reductions' and 'Access to new financial opportunities.' In the Icelandic cases, 'Cost reductions' relates mainly to the deployment of hydrogen-based fuels, as

Table 2
Strength of economic and market-based drivers in the case studies (mean stakeholder rankings indicated) on a scale 1–3. The highest ranked driver in each category is marked in yellow.

	Grundartangi	Ísafjörður	Húsavík	Luleå	Gothenburg	*Sum*
Economic						
Cost reductions	2.50	2.62	2.50	2.62	2.00	*12.2*
Access to new financial opportunities	2.21	2.17	2.00	1.85	1.83	*10.1*
Job creation	1.63	1.67	1.75	1.62	1.00	*7.7*
Increased exports	1.63	1.95	2.00	1.69	1.00	*8.3*
Market						
Market opportunities	2.50	2.56	2.50	2.15	2.75	*12.5*
Consumer demands	2.63	2.22	2.00	2.46	2.75	*12.1*
Brand & reputation	2.13	2.17	1.50	1.15	1.67	*8.6*
First mover	1.46	2.22	1.50	1.62	1.92	*8.7*
Collaboration	2.17	2.28	2.50	2.31	2.00	*11.3*
Industry Standards	1.96	2.67	2.25	1.31	na*	*8.2*
Future-proofing	2.09	2.39	2.25	2.23	2.75	*11.7*

*n/a means not listed specifically by the stakeholders in this case.

stakeholders expected these to impact fuel users rather than reduce costs for fuel producers. For instance, in Iceland, stakeholders in the fishing industry are anticipating higher prices and increased taxes for traditional fossil fuel use, and hydrogen-based fuels are expected to alleviate these burdens. Also, in the Swedish cases, the 'Cost reduction' driver is considered from a future perspective, as it is assumed that fossil fuels will become more expensive in the future due to the expected increased taxes on fossil fuels to reach climate targets. In the Swedish cases, this pertains both to development and deployment, mainly as green hydrogen and hydrogen-based energy carriers are an integrated part of industrial processes through sector coupling, particularly in the Luleå case. Also in the Gothenburg case, the stakeholders highlight that the costs of fossil alternatives will increase for users in the future making hydrogen-based fuels more attractive, but cost reductions are perceived as a somewhat less important driver compared to the other cases.

The most important market drivers, as per the stakeholder ratings, varied between the cases. For the stakeholders of Grundartangi, 'Consumer demands' for decarbonizing energy-intensive industrial processes was the most important driver. This was rated the most important for the Luleå case as well, which has a similar focus from the industrial district. The Húsavík case valued drivers from 'Market opportunities' the most. Stakeholders from Gothenburg equally ranked three drivers, including the two aforementioned drivers and 'Future-proofing', where many stakeholders perceived the need to adapt their business's maritime activities to comply with more stringent GHG emission regulations.

Table 3 outlines the strength of the main infrastructure and resource-related drivers identified by stakeholders across the five cases.

'Location' was rated as the most important driver in the 'Infrastructure' category for the three Icelandic cases and Luleå. The Grundartangi and Húsavík locations are situated in larger ports and connected to industries such as aluminum smelting and ferrosilicon production, while Ísafjörður's port caters mainly to cruise ships and does not have heavy industry nearby. The importance of location in the Luleå case mainly relates to this port being viewed as a center for the transition to green steel production and other green industrial activities using hydrogen-based fuels. In the Gothenburg case, the stakeholders mentioned that the location of the port, its size, and the related cluster is often taken for granted and that it is expected to continue to develop as it has during previous years. This could perhaps explain why 'Location' is not considered to be as important driver for Gothenburg, as for the other cases.

In the Resources category 'Energy resources' was rated highly for all

Table 3
Strength of Infrastructure and resource-related drivers in the case studies (mean stakeholder rankings indicated) on a scale 1–3. The highest ranked driver in each category is marked in yellow.

	Grundartangi	Ísafjörður	Húsavík	Luleå	Gothenburg	Sum
Infrastructure						
Location	2.46	2.67	2.25	2.54	1.75	*11.7*
Grid capacity	2.13	2.61	2.25	2.15	1.00	*10.1*
Energy security	2.13	2.39	2.00	1.15	1.90	*9.6*
Resources						
Energy resources	2.33	2.67	2.75	2.69	1.00	*11.4*
Raw material	2.04	2.17	3.00	1.85	1.00	*10.1*
People	1.96	2.06	2.50	1.00	1.67	*9.2*

three Icelandic cases as the energy landscape incorporates extensive hydropower and geothermal energy generation, resulting in an almost fossil fuel-free electricity grid. Also, Swedish electricity production is mostly fossil-free, and electricity prices are relatively low in comparison to EU averages, as is also the case in Iceland. However, energy resources are considered a more important driver by stakeholders in the Luleå case than in Gothenburg. This is likely due to to the fact that Luleå is located closer to large hydro power plants and the electricity price zone in the North of Sweden has historically had lower prices. Gothenburg, on the other hand, is in a region with a more limited electricity supply and relatively large competition for most resources. Stakeholders linked to the Húsavík site also noted the potential raw material availability (including also input goods) for producing hydrogen-based fuels. This is largely due to the availability of CO2 emissions from the nearby Bakki plant, which could be an input for future e-methanol production.

Table 4 outlines the strength of the societal, organizational, and policy-related drivers identified by stakeholders across the five cases.

Within the Organization category, stakeholders of the Húsavík, Luleå and Gothenburg cases rate 'Environmental commitments' more highly than the other two case studies. Swedish stakeholders stressed that there are internal factors that motivate their organization to reduce their environmental impact and therefore commit to the production and use of hydrogen-based fuels. In their view, this is linked to the ambitious climate policies of Sweden. Gothenburg stakeholders were particularly motivated by 'Business strategy' and 'Business case'. The reason is that the current operations of many actors connected to the Port of Gothenburg are based on fossil fuels and these actors are working to include renewable fuels, such as hydrogen-based ones, in their business models/strategies, as this will be required to be competitive in the future. The Grundartangi case in Iceland rated 'Proactive leadership and influence from owners' most strongly out of these sets of drivers, likely due to the widely publicized proposals to produce ammonia in the coming years.

'Local, regional, national, and global commitments and targets' were considered the most important (the Luleå and Ísafjörður cases) or equally important (the Húsavík and Gothenburg cases) policy-related driver as 'Policy instruments' (such as carbon taxes and/or subsidies for green hydrogen and hydrogen-based energy carriers) in all cases except for Grundartangi. In the Luleå case, which had a stronger influence from 'Local, regional, national, and global commitments and targets' many stakeholders stressed the climate targets set by the EU as a stronger driver for the development of hydrogen-based fuels than Sweden's national policy instruments.

3.2. Barriers

Table 5 outlines the strength of the economic barriers identified by stakeholders across the five case studies, and the highest ranked barrier in each category is marked in yellow in the Table 3 corresponds to the barrier being considered as a very important barrier, 2 an important barrier and 1 the factor does not constitute a barrier or is considered very minor.

On average, the Economic barriers were ranked as the strongest by stakeholders in all case studies. The main Economic barrier in all five case studies is the increased costs that can arise from various aspects of the green hydrogen fuel production or utilization process, including raw materials, production, storage, and research and development. Thus, in all cases, the stakeholders discussed that these increased costs (in comparison to fossil options) are a major barrier for the transition to hydrogen-based fuels in Nordic ports. Demand uncertainties and the competitiveness of green hydrogen-based fuels in comparison to fossil fuels were also stressed as major barriers in the Grundartangi and Gothenburg cases. The stakeholders in the Grundartangi case were hesitant about hydrogen-based fuel production due to unknown demand in Iceland's maritime sector, which constitutes the classic 'chicken and egg' dilemma, and they also reiterated the expectation that fossil fuels will remain abundant and cheaper than alternatives for some time. The stakeholders in the Gothenburg case also stressed how the uncertain demand from the maritime sector is highly important, i.e., when exactly in time there will be a demand, for what fuel types and to what extent. This demand uncertainty is linked to the lack of certainty when hydrogen-based fuels will be cost-competitive in comparison to fossil fuels. 'Competitiveness' of hydrogen-based fuels was jointly ranked with costs as the most important economic barrier in the Gothenburg case.

Table 6 outlines the strength of the technological, infrastructure, and resource-related barriers identified by stakeholders across the five case studies.

The barriers related to technology, infrastructure, and resources reveal some differences between the case studies. For example, in Sweden, 'Maturity'issues related to scalability, improved efficiency, and cost reductions from economies of scale are stressed as important

Table 4
Strength of Societal, organizational, and policy-related drivers in the case studies (mean stakeholder rankings indicated) on a scale 1–3. The highest ranked driver in each category is marked in yellow.

	Grundartangi	Ísafjörður	Húsavík	Luleå	Gothenburg	*Sum*
Society						
Stakeholder expectations	2.30	2.06	2.50	1.62	1.92	*10.4*
Social license to operate	2.25	2.33	2.75	1.15	1.92	*10.4*
Social engagement	1.96	2.17	2.50	1.08	1.00	*8.7*
Organization						
Environmental commitments	2.13	2.06	3.00	2.46	2.42	*12.1*
Business strategy	2.30	2.11	2.50	1.92	2.75	*11.6*
Business case	2.13	2.06	2.50	1.92	2.73	*11.3*
Technological availability	2.50	2.50	2.50	1.31	1.00	*9.8*
Proactive leadership and influence from owners	2.59	2.17	2.50	1.62	2.10	*11.0*
Policies						
Policy instruments	2.55	2.17	2.50	2.38	2.10	*11.7*
Local, regional, national and global commitments and targets	2.33	2.45	2.50	2.77	2.10	*12.2*

Table 5
Strength of economic barriers in the five case studies based on ranking (mean stakeholder rankings indicated) on a scale 1–3. The highest ranked barrier in each category is marked in yellow.

	Grundartangi	Ísafjörður	Húsavík	Luleå	Gothenburg	*Sum*
Economic						
Costs	2.67	2.67	2.75	2.62	2.79	*13.5*
Demand uncertainties	2.58	2.22	2.25	2.23	2.59	*11.9*
Financing	2.13	2.16	2.00	1.62	2.08	*10.0*
Competitiveness	2.46	2.33	2.50	2.15	2.79	*12.2*
Path dependency and technological lock-in	2.30	2.11	2.00	2.08	1.62	*10.1*

Table 6
Strength of technological, infrastructure, and resource-related barriers in the five case studies (mean stakeholder rankings indicated). The highest ranked barrier in each category is marked in yellow.

	Grundartangi	Ísafjörður	Húsavík	Luleå	Gothenburg	*Sum*
Technology						
Maturity	2.21	2.16	2.50	2.38	1.62	*10.9*
Security	1.92	2.06	2.25	1.15	1.00	*8.4*
Safety	2.09	1.95	2.25	1.92	1.79	*10.0*
Infrastructure						
Location	1.71	2.06	2.00	1.46	1.67	*8.9*
Infrastructure development	2.00	2.28	2.00	2.23	2.00	*10.5*
Grid capacity	2.00	2.56	2.00	2.54	2.62	*11.7*
Resources						
Energy resources	2.50	2.67	2.25	2.23	2.23	*11.9*
Raw material	1.82	1.61	2.75	1.00	1.82	*9.0*
People	2.00	1.89	2.50	1.23	1.15	*8.8*

barriers in the Luleå case, but not in the port of Gothenburg. This is explained by the contextual differences between these ports, and especially the stronger focus on mainly industrial development in the Luleå case. It is further noted that safety is seen as a slightly stronger barrier in the Icelandic cases, compared to those in Sweden. Two of the Icelandic cases, Húsavík and Ísafjörður, are located fairly near residential areas, so it is especially important to ensure safe fuel production and storage facilities, while the third Icelandic case, Grundartangi, is located on the site of two industries who stressed that the potentially volatile production of ammonia necessitates special attention to safety measures, not least so as to not affect the other industries operating in the port. Safety issues in the use phase are primarily linked to ammonia.

It is evident that 'Grid capacity' is seen as the main Infrastructure barrier in all five case studies. The need for transmitting electricity to produce hydrogen-based fuels is thus one of the largest barriers preventing development from taking place. In Luleå, Gothenburg, Grundartangi, and Ísafjörður, it was noted that some of the planned projects will not be realized unless more grid capacity is put in place. The issues related to the need for additional electricity were also revealed in the resources category, as 'Energy resources' are seen as the most important barrier in four of the five cases. Stakeholders in the Húsavík case rated barriers to 'Raw materials' and 'People' higher than the other cases. The 'Raw materials' category is considered difficult as stakeholders pertaining to the Húsavík site were unsure if the effluent CO2 emissions from the Bakki plant would be of sufficient purity to satisfy EU regulations. Moreover, relating to 'People', Húsavík, has a limited skilled workforce and would likely have to import labor to work in e-methanol production.

Table 7 outlines the strength of the societal, organizational, and policy-related barriers identified by stakeholders across the five case studies.

Barriers related to societal aspects differed substantially, especially for the two Swedish cases. In Luleå, the 'Lack of system perspective' is seen as one of the main barriers to the development of hydrogen-based fuels. The fragmented approach to addressing the transition to a low-carbon economy by the Swedish government was stressed by the stakeholders. In their opinion, this includes siloed decision-making, limited coordination, and a short-term focus. This is not as evident in the Gothenburg case, which can be explained by it being a larger port that already has multiple maritime demands, fuels, and types of storage, as well as refineries currently using hydrogen, suggesting a sense of infrastructural readiness. In contrast, at Grundartangi in Iceland, the 'Lack of system perspective' was ranked highest out of all the societal barriers, with stakeholders raising concerns about the scarce coordination between the government and maritime sector to switch fuels. Although not scored quite as highly in the other Icelandic cases of Húsavík and Ísafjörður, these same concerns were equally voiced by stakeholders.

Regarding barriers related to organizational aspects, some differences were apparent between the case studies. In Gothenburg, the 'Lack of operational space' was seen as a clear hindrance of development, which can be explained by the limited possibilities to expand the port area. Also, in the Ísafjörður case, lack of space for production and storage was communicated by stakeholders, while in the Luleå case, the

Table 7
Strength of societal, organizational, and policy-related barriers in the five case studies (mean stakeholder rankings indicated). The highest ranked barrier in each category is marked in yellow.

	Grundartangi	Ísafjörður	Húsavík	Luleå	Gothenburg	*Sum*
Society						
Public opinion	2.04	1.78	2.50	1.69	1.54	*9.6*
Lack of system perspective	2.30	2.06	1.75	2.69	1.15	*10.0*
Protecting nature	1.75	1.78	2.00	1.15	1.00	*7.7*
Lack of external stakeholders	1.88	1.89	1.75	2.31	1.00	*8.8*
External stakeholders with opposite interests	2.04	2.11	2.00	1.38	1.00	*8.5*
Lack of knowledge	2.13	2.11	2.50	2.31	1.15	*10.2*
Organizational						
Lack of operational space	1.38	2.33	1.00	1.38	2.59	*8.7*
Resistance to change	2.08	2.17	1.75	1.92	1.54	*9.5*
Business case	1.92	2.00	1.75	2.08	2.08	*9.8*
Long timelines	2.33	2.34	2.00	2.31	1.54	*10.5*
Lack of stakeholders	1.92	1.78	1.50	1.00	1.00	*7.2*
Stakeholders with opposite interests	1.92	2.06	1.50	1.31	1.00	*7.8*
Policies						
Policy instruments	1.91	1.84	2.50	2.00	1.00	*9.3*
Lack of policy instruments	2.64	2.33	2.50	2.69	2.33	*12.5*
Permitting	1.82	2.11	2.50	1.77	1.62	*9.8*
Certifications	1.78	2.00	2.50	1.00	n/a*	*7.3*
Lack of targets	2.18	1.33	2.25	n/a*	n/a*	*5.8*

*n/a means not lifted specifically by the stakeholders in this case.

area linked to the port has already been prepared for new industrial activities. In all the Icelandic cases and the Luleå case, 'Long timelines' were the most highly rated organizational barrier. In this context, stakeholders discussed problems with making long-term decisions, which are needed to invest in new technology and infrastructure when there are many uncertainties involved.

Finally, in all five cases, 'Lack of policy instruments' was seen as a major barrier in the policy category. In all cases, stakeholders discussed a lack of support for switching to green hydrogen and hydrogen-based energy carriers, with insufficient policy instruments, especially economic, to guide and incentivize developments. In the Icelandic case also the governmental focus on technology neutrality hinders the development. Even though some of the barriers are important in all cases, there is variation between the drivers and their intensity for each case study, reflecting the differences and multidimensional characteristics of the ports.

4. Discussion and policy implications

This study has systematically explored and compared the relative strength of drivers and barriers pertaining to the development of green hydrogen and hydrogen-based hubs in five selected ports in Iceland and Sweden. The discussion summarizes the context-specific drivers and barriers for each hub and development level. Then, it introduces the

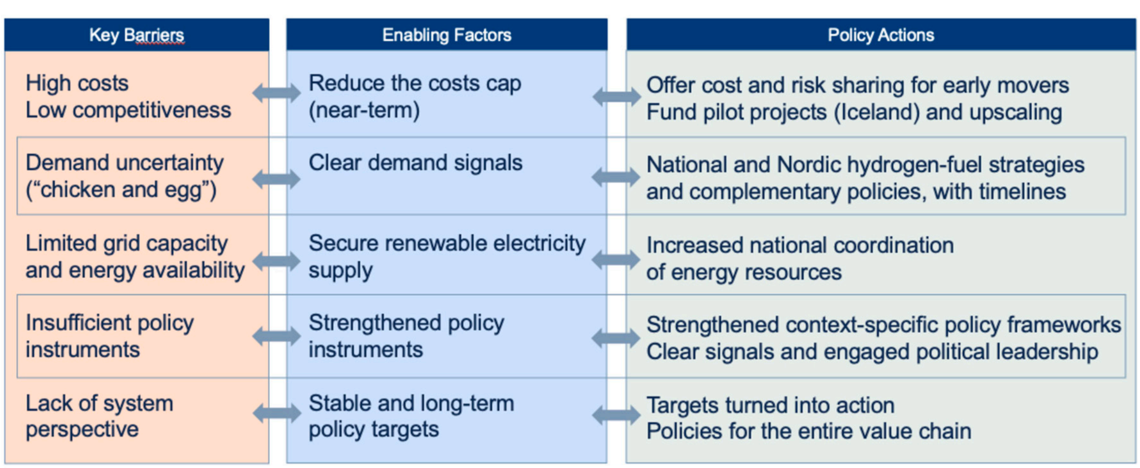

Fig. 3. Overview of key barriers, key enabling factors, and main policy actions for breaking the green hydrogen deadlock in Nordic ports. Cost gap refers to the cost difference between green hydrogen-based fuels and fossil fuels and fossil fuel-based options. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

enabling factors necessary to overcome key barriers that are common across the Nordic cases. An overview of key barriers and enabling factors, and the main policy implications are depicted in Fig. 3.

4.1. Context-specific drivers for hydrogen-hubs in the Nordics

In the multi-purpose port of Gothenburg, market and organizational aspects (e.g., business case and strategy) are more prominent due to the port's established industrial cluster and focus on adapting existing fossil-based operations [34]. Stakeholders here emphasized their readiness for emerging demand, interconnected with the future proofing that is necessary to maintain competitiveness. Conversely, in Luleå and the three Icelandic cases, resource (energy and raw materials) and policy drivers are relatively more prominent, reflecting proximity to renewable sources and industrial synergies. The availability of energy resources is reliant on policies on the national and local level. This underscores the importance of establishing policies to increase energy resources at hub sites in the conceptual and planned development stages of hubs, as hydrogen-based fuels cannot be developed without appropriate available energy resources. Societal drivers, such as local acceptance and collaboration, appear more influential in the Icelandic cases, potentially due to smaller-scale communities and tourism dependencies, yet they interconnect with all others by fostering the stakeholder coordination deemed essential for hydrogen hub development [9,22]. The relative importance of societal drivers can possibly also be explained by the Icelandic cases being in more early hub development stages, either conceptual or planned, compared to the Swedish cases that are in the initiated hub stage. Table S6 in the appendix illustrates the interplay between drivers, hub development stages and contextual factors according to the text in this section.

Several types of drivers are perceived as important across all five assessed cases, spanning market, economic, resource, organizational, and policy-related dimensions, in accordance with the findings of Buonomano et al. [29]. From an overall perspective, new market opportunities and expected cost reductions, which are closely intertwined with anticipated future consumer demands, emerge as some of the most important drivers, especially for the Swedish cases which have hubs in the initiated development phase. These are reinforced by environmental targets and commitments at multiple scales (global, regional, national, local, and company levels), which stakeholders from all cases frequently cited as strong motivating forces. The interconnectedness of these drivers is a critical insight from the stakeholder's perceptions. Market opportunities do not exist in isolation; they are amplified by consumer demands, which in turn are driven by escalating regulatory pressures and environmental commitments [8,19]. Expected cost reductions further link these elements, as stakeholders anticipate that rising fossil fuel taxes and carbon pricing, stemming from policy instruments such as the EU Emission trading system (ETS) and carbon taxes, will enhance the competitiveness of green hydrogen-based fuels over time [70,71]. This creates a virtuous cycle that needs to be unlocked, where international and Nordic national policy-driven commitments (e.g., Nordic national roadmaps or similar; [13–17] stimulate market demand, which can then unlock economic opportunities and justify investment in resource-intensive production and move the hydrogen hub cases further than the planned and initiated development phases.

4.2. Context-specific barriers for hubs in the Nordics

Stakeholders across all five cases identified similarities in the primary barriers to hydrogen-based fuel development and deployment that supersede context-specific factors and could be features of hub developmental stages. Economic factors, particularly increased costs compared to fossil fuels, rated as the most significant overall (followed by demand uncertainties and competitiveness). These costs span raw materials, production, storage, distribution, and research and development, rendering hydrogen-based fuels currently uncompetitive with abundant, low-cost fossil alternatives [8,20,21]. This finding is applicable regardless of which development phase the hydrogen hub is in. Closely intertwined are insufficient or non-existent policy instruments, including e.g., economic incentives, which were highlighted in every case as critical impediments to guiding and funding the transition. However, to overcome such barriers, context-specific policies, for example, supporting relevant pilot projects in the conceptual and planned phases for Icelandic cases or funding support possibilities with built-in-flexibility, allowing for several different measures relevant for the initiated phase of the Swedish cases to be covered, are important for further hub development. The concept of context-specific policy frameworks means that the policies need to reflect context-specific factors covering local to national characteristics, as well as support several different aspects of a hydrogen hub depending on what is needed for its stage and specific context. The earlier mentioned Swedish support system "Klimatklivet" represents one example of the latter. Infrastructure and resource constraints, especially limited electricity grid capacity and energy availability, further compound these challenges, forming a tightly interconnected web of contextual obstacles that perpetuates the green hydrogen deadlock [8,20,72,73].

The interconnectedness of several of these barriers is central to understanding the stalled progress and what hinders further hydrogen hub development and establishment. High costs do not operate in isolation; they are amplified by demand uncertainties – the classic 'chicken-and-egg' dilemma – where producers hesitate without assured maritime uptake, and shipowners delay adoption in the absence of cost-competitive, readily available fuels and lack of appropriate port infrastructure [19,74,75]. This uncertainty is deeply linked to inadequate policy support, as without robust subsidies, carbon pricing, or take-off agreements, fossil fuels will retain their economic edge for some time despite IMO and EU decarbonization mandates [5,6,71,76]. As identified in this inquiry, electricity grid constraints exacerbate this cycle. There is the possibility that rapid electricity demand growth from 'greening' industries risks outpacing supply, potentially constraining production. This is especially relevant for northern Sweden, which currently exports electricity but may become a net importer by 2035, as electricity demand is projected to double, driven mainly by planned green industrial initiatives [77].

Alamoush [27] highlights key determinants for port decarbonization beyond technological challenges. The determinants of interorganizational relationships, capacities and economic conditions, complexity, and size impact the different cases capacities to develop hydrogen hubs. The context-specific differences between the cases reveal how these interconnections vary locally. Table S7 in the appendix provides an illustration of the interplay between context-specific and developmental factors for the barriers. In Gothenburg, operational space constraints and uncertain maritime demand intensify cost and policy barriers within a mature, space-limited port [34]. In Luleå and the three Icelandic cases, energy and electricity grid bottlenecks are more acute, partly due to infrastructure issues but also due to ambitious industrial scaling in the case of 840 MW ammonia production facility planned at Grundartangi [51] and several industrial plans in the Luleå region. Safety concerns, which were rated higher in Iceland, particularly for ammonia were also confirmed in the Gothenburg case. They link to factors ranging from technical immaturity to societal and regulatory barriers, especially near residential or tourism areas. Across all sites, the lack of a systemic perspective in governance hinders coordination, allowing the siloed decision-making described by Corcoran et al. [8] to perpetuate misaligned incentives and infrastructure development delays.

4.3. Enabling factors and policy implications

The dualistic nature of drivers and barriers – where the same categories (costs, policies, energy resources) emerge as both drivers and barriers – reflects perspective-dependent tensions and systemic uncertainties [78]. For example, stakeholders anticipate future cost reductions via policy-driven carbon taxes and scale-up, yet market-related barriers such as current low carbon pricing, legacy fossil infrastructure, lobbying from the fossil fuel industry and limited production volumes sustain high costs as a dominant barrier [8,70]. Similarly, renewable energy abundance is a perceived driver in Iceland and northern Sweden, but insufficient grid expansion and competing sectoral demands (e.g., steel de-fossilization in Luleå via HYBRIT; [59]) transform it into a binding constraint. Long permitting timelines and fragmented governance further entrench these interconnections, delaying infrastructure developments and reinforcing investor caution [58].

The empirical evidence from these case studies reveals a clear policy imperative: costs, competitiveness, demand uncertainty, grid capacity and the linked access to renewable electricity, and insufficient policy instruments (independent of development stage) form the main barriers that must be dismantled in tandem to unlock hydrogen hubs and move them forward in the development stages. Notably, these barriers are present in all cases, regardless of context-specific factors, which suggests they are shared challenges that could be experienced when developing hydrogen hubs in the Nordics or worldwide. These barriers are not isolated hurdles but deeply interdependent since high costs will persist without demand certainty, grid bottlenecks constrain scale-up, and weak policy fails to bridge either gap. Addressing one in isolation risks perpetuating the “green hydrogen deadlock” [20]. Breaking it requires addressing root causes holistically. Without coordinated context-specific policy frameworks that simultaneously tackle cost competitiveness, secure energy supply, and stimulate demand, incremental progress risks stalling. As an example, several stakeholders linked to the Port of Gothenburg emphasize that the transition in this region is slowed down by the uncertain demand and cost for green hydrogen-based fuels which are connected to the lack of sufficient policies [76]. In this case, policies for supporting the upscaling of hydrogen-based fuels and for securing demand are called for. The transition of Nordic ports to become hydrogen hubs demands integrated strategies that align economic, technical, and regulatory levers, which, based on the inquiry's five case studies, is precisely where the current barriers remain most entangled.

Thus, the overall identified enabling factors for the case studies, interconnected in many ways, include reduced cost and clearer demand for hydrogen-based fuels (or higher cost for fossil fuels) also in the near term, a secure supply of renewable electricity for hydrogen-based fuel projects, and policy instruments that can support these pursuits and support the transition to hydrogen-based fuels in the Nordic countries in the short-term (illustrated in Fig. 3). These enabling factors are in line with the enabling factors developed for comparing the national prerequisites for development and delivery of low-emission hydrogen production projects in a global context presented by IEA [11]. As hydrogen-fuel related and context-specific policy frameworks might influence other enabling factors, they are vital for both development and deployment of such fuels, as also indicated by IEA [11] where policies had the highest relative importance among the enabling factors.

In terms of policy needs, recommendations (summarized in Fig. 3) are specified to support the development of hydrogen hubs linked to Nordic ports based on the case study outcomes. It is important that policies reflect context-specific factors covering local to national characteristics as well as the development stage of the hydrogen hub. For example, the Icelandic cases that are in the conceptual and planned development phases are more in need of advancement policies such as the financing of pilot plants in the hubs. The Swedish cases, that are in the initiated development phases, are more in need of policies that are aimed at upscaling and securing demand, key aspects in moving towards ultimate establishment. The current policy framework also needs to be strengthened in general and include policies that support the entire value chain of hydrogen-based fuels, development phases of hydrogen hubs, as well as different types of fuels (as indicated by the perceived importance of the lack of policies in all case studies). It is key to secure demand for hydrogen-based fuels in the short-term, i.e., there is a need to complement the EU policies with national or Nordic policies that focus on promoting national and regional demand in the coming years and support early movers. This has also been argued for by DNV et al. [19], and is further confirmed by Statkraft's decision, earlier leading the planned hydrogen production plant in the Port of Gothenburg, to stop their activities in the hydrogen area partly due to difficulties in finding off-takers prepared to absorb the cost for their product in the near-term [79]. Also, Flodén et al. [76] confirm that there is insufficient support for retrofitting or changing ship fleets in the short to mid-term. However, ambitious science-based targets on a company level might support investments, which may also be undertaken in the short-term, given that the companies strive to fulfil their targets in the short-term – the Swedish truck manufacturer Scania investing in the Stegra green steel project being one such example).

In Iceland and Sweden there is a need for clearer signals and political leadership in the hydrogen-based fuel area, as overall goals and targets must be translated into actions for development and deployment to be realized. This was indicated partly by the ‘Lack of system perspective’ barrier, and overcoming this is especially important given the currently uncertain global situation, exemplified by indications at the EU level that the hydrogen targets will not be met [80] and the decision in October 2025 to postpone by one year the decision on a global IMO policy for maritime fuels (the so-called Net-Zero Framework) [81]. In Iceland, there are ambitious targets for hydrogen-based fuels and policy proposals, but there is a lack of coherence in planning, which means that policy suggestions have not been implemented in practice [8,16]. On the other hand, in Sweden, the national targets lack a quantitative level, mainly highlighting hydrogen as a driver for the transition to a fossil-free energy system [62].

The interest and initiatives for different types of hydrogen-based fuels also need to be aligned with expected demand. This can be exemplified by the Icelandic situation, where there is an interest in producing ammonia while the Icelandic maritime industries are currently more interested in methanol [8,16]. In Sweden, there are several parallel tracks with hydrogen for industrial applications and e-fuels for shipping and aviation including methanol and ammonia [15], but a lack of clear governmental guidance.

The cost gap between hydrogen-based fuels and fossil fuels needs to be reduced [19]. Besides promoting demand, there also needs to be additional funding support for relevant pilot projects in Iceland (as mentioned earlier), whereas in Sweden the support should be directed towards upscaling of hydrogen-based fuel-related projects. The market will not be able to solve the required upscaling on its own nor make sure that the demand is aligned with the supply. The related cost and other risks for early movers must be shared with society.

In addition, increased national or regional coordination on energy resources and electricity availability, including grid capacity, is called for in the Nordic countries to reduce the risk of electricity shortages [82]. Linked to this, it is important to gain an increased understanding of how industries, ports, and society can become better connected to reduce costs and investment risks [23]. Linked to several of the assessed case studies, there are considerable opportunities for innovative sector couplings and energy system integration, which, if realized, would reduce the cost of hydrogen-based fuels. However, policies must more clearly support and unlock this potential for industrial symbiosis. There is also the possibility of linking the development of hydrogen hubs more clearly to the energy security issue, which has the potential to become a more important driver in the Nordic countries in the future. This is acknowledged by the Swedish Government which recognizes the importance of efficient integration of hydrogen with electricity and heating systems to enhance the security of supply [83]. Policy support should also be available across the hydrogen value chain. Support for production must come hand in hand with demand stimulations and support for infrastructure investments, e.g., in ports.

Hydrogen-based fuels are often linked to complex processes, and in general, more knowledge is needed among regulators and investors on hydrogen-based fuels and their complex nature. This is also true for potential early movers, represented by established energy companies that are based on another core business, for projects to be realized and successful. For the Nordic countries to become global frontrunners, a stronger policy framework needs to be put in place soon as the development of hydrogen-based fuels in countries such as China is accelerating [33,84].

Without more context-specific efforts from the government, barriers to hydrogen-based fuels can create a complex system characterized by fragmented efforts and information gaps among stakeholders [8,20]. This lack of coordination can perpetuate the "green hydrogen deadlock" [20], where progress is hindered by the inability of stakeholders, each focused on specific sub-sets of issues, to effectively collaborate and share knowledge [8,20]. As shown in the case studies, frontrunners in the hydrogen-based fuel area are crucial for the implementation and further development of hydrogen-based hubs, but the political and market conditions must also be in place for realization.

4.4. Limitations and future work

Achieving comparable qualitative datasets and synthesizing results with potential causal explanations is challenging [42]. To mitigate this, participants were presented with definitions of the drivers and barriers as shown in Tables S4 and S5 in the Appendix. The quantitative ratings of the drivers and barriers from the 64 interviews relied on stakeholder perceptions rather than any hard data, for example, on grid congestion and techno-economic feasibility. While the ranking sessions demonstrate stakeholder perceptions of the relative strengths of drivers and barriers for hydrogen-based fuel hubs in the Nordic region, the extent of the rankings should be interpreted with appropriate caution. Due to scheduling conflicts, some stakeholders in Iceland could not attend both the interviews and rankings sessions. The omission of their perspectives potentially impacts the results. The reference to mean ratings can, however, mask outliers and this study was not a longitudinal one, and thus it was not possible to assess how perceptions may have shifted in recent years, for instance, due to the emergence of new policies, but this could be an interesting avenue for future research. The methods could have included an established assessment structure, such as a Delphi survey [85]. However, the Delphi method was rejected as it is better-suited when seeking a consensus, rather than eliciting multiple perspectives, which was the aim of this study [86].

More specific studies on relevant policy instruments and policy mixes for the Nordic countries according to hydrogen hub development stages are needed. Linked to this, the impact in the Nordic countries of policies introduced to promote hydrogen on an EU and national level should be assessed, such as the competitive auctions for hydrogen production supported by the EU Innovation Fund via the European Hydrogen Bank. Further research should explore the drivers and barriers linked to development phases of hydrogen hubs. Also, the importance of national and EU strategies for hydrogen (or lack of them) should be evaluated. The role of various stakeholders and successful initiatives for realizing hydrogen-based fuel hubs in the Nordic countries, as well as green shipping corridors, also warrants further investigation. It is also important to set the development in the Nordic countries in relation to the development of hydrogen-based fuels in the rest of the world.

5. Conclusions

This comparative study investigated how stakeholders perceive the relative strength of drivers and barriers, shaping the development of hydrogen-based fuel hubs within five Nordic ports. The analysis identifies both similarities and differences across the ports, noting context-specific factors and clarifying the pathway from hub conceptualization to implementation. For instance, stakeholders for the port of Gothenburg perceived market and organizational drivers as being stronger than Luleå and the Icelandic cases. All cases rated environmental targets and commitments at multiple scales as strong drivers for pursuing green hydrogen-based fuels.

The differences in the strength of barriers reflect specific contextual factors, such as Iceland's limited grid capacity and Sweden's already established industrial synergies and sector coupling. Each case study is part of a complex energy system in different port settings, involving features such as industrial production, district heating, and various demands, which require considerations and coordination when realizing the implementation of green hydrogen and hydrogen-based energy carriers. Energy system integration and sector coupling are enablers in port decarbonization and thus crucial for realizing the hydrogen hub concept in Nordic ports.

Despite the differences between ports and hub development stages, several similarities dominated the barriers: High costs, low competitiveness, limited grid capacity, and insufficient policy instruments emerged as highly rated barriers in all five Nordic ports. These are not isolated hurdles, but interconnected barriers that both exacerbate the green hydrogen deadlock and underscore its magnitude within the Nordic region. Stakeholders stressed a lack of support for switching to hydrogen-based fuels, with no case study exhibiting adequate economic incentives to enable the cost gap with fossil fuels to be bridged.

Critically, several of the same categories emerged as dualistic drivers and barriers in this study. Energy resources drive the general perception of feasibility in Iceland and Luleå, yet become barriers when demand outpaces supply; various policy commitments from the IMO, EU, and individual nations motivate action but falter without sufficient economic support; market opportunities and customer demand are top-rated drivers yet remain static amid cost and regulatory uncertainty. It is evident that although the market and its stakeholders are critical to the potential establishment of hydrogen hubs, it is insufficient to resolve the green hydrogen deadlock. It is necessary for national governments, in the Nordic region and elsewhere, to act decisively in providing the necessary economic support and leadership. Breaking the deadlock can include policy measures tailored to the development stage of a hub, such as the funding of pilot projects and research and development programs for conceptual hubs to reach the initiated hub stage. For initiated hubs, support for up-scaling and demand stimulations are needed, which could involve consumer guarantees for hydrogen-based fuel projects, levying ever increasing carbon taxes on fossil fuels, and creating comprehensive holistic roadmaps for the establishment of hydrogen hubs. The latter should be according to prescribed timescales and aligned with EU, IMO, and national policy imperatives for the decarbonization of the maritime and industrial sector.

CRediT authorship contribution statement

Cary Kincaid Corcoran: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Julia Hansson:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Linda Wårell:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David Cook:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization. **Brynhildur Davíðsdóttir:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Lára Jóhannsdóttir:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization. **Cecilia Wallmark:** Writing – review & editing, Validation, Project administration, Funding acquisition, Conceptualization. **Joakim Lundgren:** Writing – review & editing, Validation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Cary Kincaid Corcoran reports financial support was provided by Nordic Energy Research. Julia Hansson reports financial support was provided by Nordic Energy Research. Linda Warell reports financial support was provided by Nordic Energy Research. David Cook reports financial support was provided by Nordic Energy Research. Brynhildur Davidsdottir reports financial support was provided by Nordic Energy Research. Lara Johannsdottir reports financial support was provided by Nordic Energy Research. Cecilia Wallmark reports financial support was provided by Nordic Energy Research. Joakim Lundgren reports financial support was provided by Nordic Energy Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2026.104848.

Data availability

Data will be made available on request.

References

[1] P.R. Shukla, et al., Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2022, https://doi.org/10.1017/9781009157926.

[2] United Nations Environment Programme, Emissions Gap Report 2024: No More Hot Air … Please! With a Massive Gap Between Rhetoric and Reality, Countries Draft New Climate Commitments, , United Nations Environment Programme, Nairobi, 2024, https://doi.org/10.59117/20.500.11822/46404.

[3] United Nations Environment Programme, Emissions Gap Report 2025: Off Target, Continued Collective Inaction Puts Global Temperature Goal at Risk, United Nations Environment Programme, Nairobi, 2025, https://doi.org/10.59117/20.500.11822/48854.

[4] M. Crippa, et al., GHG emissions of all world countries, 2025, Publications Office of the European Union (2025) 1–293. Accessed: Jan. 14, 2026. [Online]. Available: https://data.europa.eu/doi/10.2760/9816914.

[5] International Maritime Organization, 2023 IMO Strategy on Reduction of GHG Emissions from Ships, Accessed: Jan. 16, 2026. [Online]. Available: https://www.imo.org/en/ourwork/environment/pages/2023-imo-strategy-on-reduction-of-ghg-emissions-from-ships.aspx, 2023.

[6] European Commission, Sustainable and Smart Mobility Strategy, putting European transport on track for the future, . Accessed: Jan. 16, 2026. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0789, 2020.

[7] DNV, Hydrogen Forecast to 2050, Accessed: Jan. 14, 2026. [Online]. Available: https://www.iims.org.uk/dnvs-published-a-forecast-and-insight-about-the-development-and-role-of-hydrogen-in-the-energy-transition/, 2022.

[8] C.K. Corcoran, B. Davíðsdóttir, D. Cook, L. Jóhannsdóttir, Drivers and barriers for the development and deployment of hydrogen based fuels for the maritime sector, a case study from Iceland, Int. J. Hydrog. Energy 162 (2025) 150367, https://doi.org/10.1016/j.ijhydene.2025.150367.

[9] T. Notteboom, H. Haralambides, Seaports as green hydrogen hubs: Advances, opportunities and challenges in Europe, Marit. Econ. Logist. 25 (2023) 1–27, https://doi.org/10.1057/s41278-023-00253-1.

[10] M. Lehtveer, S. Brynolf, M. Grahn, What future for electrofuels in transport? Analysis of cost competitiveness in global climate mitigation, Environ. Sci. Technol. 53 (2019) 1690–1697, https://doi.org/10.1021/acs.est.8b05243.

[11] International Energy Agency, Global Hydrogen Review 2025, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2025, 2025.

[12] European Commission, A hydrogen strategy for a climate neutral Europe, Accessed: Jan. 16, 2026. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0301, 2020.

[13] Government of Denmark, Køreplan for et grønt Danmark, . Accessed: Jan. 14, 2026. [Online]. Available: https://regeringen.dk/aktuelt/tidligere-publikationer/koereplan-for-et-groent-danmark/, 2024.

[14] J. Laurikko, et al., "National Hydrogen Roadmap for Finland," TEKES, Tech. Rep, 2020.

[15] Swedish Energy Agency, Förslag till Sveriges nationella strategi för vätgas, elektrobränslen och ammoniak, . Accessed: Jan. 14, 2026. [Online]. Available: https://energimyndigheten.a-w2m.se/System/TemplateView.aspx?p=Arkitektkopia&id=93ccce277b384104bd8c6f64b499575f&q=Sveriges%20nationella%20strategi%20f%C3%B6r%20v%C3%A4tgas%2C%20elektrobr%C3%A4nslen&lstqty=1, 2021.

[16] Government of Iceland, Hydrogen and E-fuels Roadmap for Iceland, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.government.is/library/Files/240102_URN_RoadmapForIceland_V6.pdf, 2024.

[17] Government of Norway, Regjeringens hydrogenstrategi, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.regjeringen.no/no/dokumenter/regjeringens-hydrogenstrategi---pa-vei-mot-lavutslippssamfunnet/id2704860/, 2020.

[18] Hydrogen Council, "Hydrogen Insights 2024," McKinsey & Company, Accessed: Jan. 14, 2026. [Online]. Available: https://hydrogencouncil.com/en/hydrogen-insights-2024/, 2024.

[19] DNV, et al., Fuel Transition Roadmap for Nordic Shipping, Accessed: Jan. 14, 2026. [Online]. Available: https://futurefuelsnordic.com/the-fuel-transition-roadmap-for-nordic-shipping/, 2024.

[20] IRENA, Green hydrogen strategy: a guide to design, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.irena.org/Publications/2024/Jul/Green-hydrogen-strategy-A-guide-to-design, 2024.

[21] J.G. Segovia Hernández, et al., Green hydrogen production for sustainable development: a critical examination of barriers and strategic opportunities, RSC Sustain. 3 (2025) 134–157, https://doi.org/10.1039/D4SU00630E.

[22] S. Damman, M. Steen, A socio-technical perspective on the scope for ports to enable energy transition, Transp. Res. Part D: Transp. Environ. 91 (2021) 102691, https://doi.org/10.1016/j.trd.2020.102691.

[23] C. Gabrielii, et al., Energy systems integration and sector coupling in future ports: a qualitative study of Norwegian ports, Appl. Energy 380 (125003) (2025), https://doi.org/10.1016/j.apenergy.2024.125003.

[24] Bjerkan, et al., Actors in energy transitions: transformative potentials at the intersection between Norwegian port and transport systems, Energy Res. Soc. Sci. 72 (2021) 101868, https://doi.org/10.1016/j.erss.2020.101868.

[25] P. Upham, P. Maristany, The global yet local nature of energy imaginaries: the cases of Dutch and Spanish hydrogen valleys, Energy Res. Soc. Sci. 123 (2025) 104028, https://doi.org/10.1016/j.erss.2025.104028.

[26] Jodry, et al., Resilience analysis for energy foresight scenarios: addressing the deep uncertainties of hydrogen deployment in industrial hubs, Energy Policy 214 (115258) (2026), https://doi.org/10.1016/j.enpol.2026.115258.

[27] A.S. Alamoush, Harboring change: exploring the multifaceted and complex determinants of decarbonizing ports, Energy Res. Soc. Sci. 118 (2024) 103751, https://doi.org/10.1016/j.erss.2024.103751.

[28] Damman, et al., Policies shaping energy transitions in ports and harbours: a 'whole systems' perspective from Norway, Energy Res. Soc. Sci. 125 (2025) 104101, https://doi.org/10.1016/j.erss.2025.104101.

[29] A. Buonomano, et al., Future pathways for decarbonization and energy efficiency of ports: modelling and optimization as sustainable energy hubs, J. Clean. Prod. 420 (138) (2023), https://doi.org/10.1016/j.jclepro.2023.138402.

[30] T.T.N. Minh, et al., Revisiting port decarbonization for advancing a sustainable maritime industry: insights from bibliometric review, Sustainability 17 (4302) (2025), https://doi.org/10.3390/su17104302.

[31] P. Halpe, M. Adams, T.R. Walker, Challenges and opportunities for ports in achieving net zero emissions in maritime transport, Transp. Res. Interdiscip. Perspect. 30 (101379) (2025), https://doi.org/10.1016/j.trip.2025.101379.

[32] P.S.L. Chen, et al., A review on ports' readiness to facilitate international hydrogen trade, Int. J. Hydrog. Energy 48 (2023) 17351–17359, https://doi.org/10.1016/j.ijhydene.2023.01.220.

[33] P.S.L. Chen, et al., Opportunities and challenges of hydrogen ports: An empirical study in Australia and Japan, Hydrogen 5 (2024) 436–458, https://doi.org/10.3390/hydrogen5030025.

[34] L. Styhre, et al., "Role of port authorities in green energy supply for transport chains," IVL Swedish Environmental Research Institute, Stockholm, Rep. B 2490, . Accessed: Jan. 14, 2026. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-4458, 2024.

[35] A. Odenweller, F. Ueckerdt, The green hydrogen ambition and implementation gap, Nat. Energy 10 (2025) 110–123, https://doi.org/10.1038/s41560-024-01684-7.

[36] Y. Chen, A. Hexeberg, K.E. Rosendahl, T.F. Bolkesjø, Long term trends of Nordic power market, a review, WIREs Energy Environ. 10 (2021), https://doi.org/10.1002/wene.413.

[37] Nordic Energy Research, Hydrogen, electrofuels, CCU and CCS in a Nordic context, 2022, https://doi.org/10.6027/NER2022-02.

[38] Fossilfritt Sverige, Vätgasstrategi för fossilfri konkurrenskraft, . Accessed: Jan. 14, 2026. [Online]. Available: https://fossilfrittsverige.se/strategier/vatgas/, 2021.

[39] R. Jayabal, Hydrogen energy storage in maritime operations, a pathway to decarbonization and sustainability, Int. J. Hydrog. Energy 109 (2025) 1133–1144, https://doi.org/10.1016/j.ijhydene.2025.02.207.

[40] M.Q. Mohd Tamam, C. Dansoh, A. Panesar, The roadmap to carbon neutrality for the maritime industry, an insight into various routes to decarbonise ship engines, Energy Convers. Manag. 27 (101184) (2025), https://doi.org/10.1016/j.ecmx.2025.101184.

[41] Global Maritime Forum, Oceans of opportunity, supplying green methanol and ammonia at ports, . Accessed: Jan. 14, 2026. [Online]. Available: https://globalmaritimeforum.org/report/oceans-of-opportunity-supplying-green-methanol-and-ammonia-at-ports/, 2024.

[42] J. Goodman, J. Marshall, Problems of methodology and method in climate and energy research: socialising climate change? Energy Res. Soc. Sci. 45 (2018) 1–11, https://doi.org/10.1016/j.erss.2018.08.010.

[43] Hafnir Ísafjarðaabær, Port of Ísafjörður, Accessed: Jan. 16, 2026. [Online]. Available: https://port.isafjordur.is/, 2026.

[44] Ísafjarðarbær, Ísafjörður Town, . Accessed: Jan. 16, 2026. [Online]. Available: https://www.isafjordur.is/, 2026.

[45] Norðurþing, Norðurþing, . Accessed: Jan. 16, 2026. [Online]. Available: https://www.nordurthing.is/, 2026.

[46] Landsvirkjun, Turning emissions into green methanol to decarbonize industries, . Accessed: Jan. 16, 2026. [Online]. Available: https://www.landsvirkjun.com/news/turning-emissions-into-green-methanol, 2022.

[47] Árbakki, Explore business opportunities in Northern Iceland n.d. Accessed: Jan. 16 (2026) [Online]. Available: https://arbakkiecopark.com/units/.

[48] Faxaflóahafnir, Grundartangi, Tangabakki, . Accessed: Jan. 16, 2026. [Online]. Available: https://www.faxafloahafnir.is/, 2024.

[49] Grundartangi Development Association, Eco industrial park emphasising circularity, . Accessed: Jan. 16, 2026. [Online]. Available: https://www.grundartangi.is/eco-industrial-park, 2026.

[50] Ventisfélagið Katanes, The Katanes hydrogen project will provide Iceland with a clean source of energy in the form of green hydrogen and ammonia, . Accessed: Jan. 16, 2026. [Online]. Available: https://www.katanes.is/english, 2026.

[51] EFLA, Connection to Grundartangi, Accessed: Jan. 16, 2026. [Online]. Available: https://assets.ctfassets.net/8k0h54kbe6bj/6AweBl9eJdYxXBVTLKbmSv/ffe4e09f28509b2b0f790adb72f44650/Connections_Grundartangi_summary2023.pdf, 2023.

[52] Göteborgs Hamn, Om Göteborgs Hamn, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.goteborgshamn.se/om-oss/, 2026.

[53] St1, Verksamhetsområden, . Accessed: Jan. 14, 2026. [Online]. Available: https://st1.se/om-oss/foretagsinformation/verksamhetsomraden, 2026.

[54] L. Styhre, et al., “Role of port authorities in green energy supply for transport chains,” IVL Swedish Environmental Research Institute, Rep. B 2490, . Accessed: Jan. 14, 2026. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-4458, 2024.

[55] Göteborgs Hamn, Laddinfrastruktur och alternativa drivmedel, Accessed: Jan. 14, 2026. [Online]. Available: https://www.goteborgshamn.se/erbjudande/trafik/vag/alternativadrivmedel/, 2026.

[56] Göteborgs Hamn, Göteborgs hamn och Rotterdams hamn startar grön korridor för hållbar sjöfart, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.mynewsdesk.com/se/goteborgs_hamn/pressreleases/goeteborgs-hamn-och-rotterdams-hamn-startar-groen-korridor-foer-haallbar-sjoefart-3211207, 2022.

[57] J. Hansson, et al., HOPE, Hydrogen fuel cells solutions in Nordic shipping, IVL Swedish Environmental Research Institute, Gothenburg, 2023.

[58] M. Vendt, C. Wallmark, “Prestudy H2ESIN, Hydrogen, energy system and infrastructure in Northern Scandinavia and Finland,” RISE Research Institutes of Sweden, Accessed: Jan. 14, 2026. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-61532, 2022.

[59] V. Vogl, M. Åhman, L.J. Nilsson, The making of green steel in the EU, a policy evaluation for the early commercialization phase, Clim. Pol. 21 (2021) 78–92, https://doi.org/10.1080/14693062.2020.1803040.

[60] Uniper, BotnialänkenH2, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.uniper.energy/sv/sverige/kraftverk-i-sverige/elektrobranslen-i-sverige/botnialankenh2, 2026.

[61] LKAB, Progress in Luleå for the investment in critical minerals, . Accessed: Apr. 29, 2026. [Online]. Available: https://lkab.com/en/news/progress-in-lulea-for-the-investment-in-critical-minerals/, 2026.

[62] Government of Sweden, Ett klimatpolitiskt ramverk för Sverige, Prop. 2016/17: 146. Accessed: Jan. 14, 2026. [Online]. Available: https://www.regeringen.se/rattsliga-dokument/proposition/2017/03/prop.-201617146, 2017.

[63] M. Edvall, L. Eriksson, S. Skärhem, Handlingsplan: Regional samverkan kring vätgas, Accessed: Jan. 14, 2026. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-68137, 2023.

[64] European Environment Agency, Share of renewable energy in final energy consumption, Accessed: Jan. 14, 2026. [Online]. Available: https://www.eea.europa.eu/en/europe-environment-2025/countries/iceland/renewable-energy-sources, 2025.

[65] Swedish Energy Agency, Energiindikatorer, . Accessed: Jan. 14, 2026. [Online]. Available: https://energimyndigheten.a-w2m.se/System/TemplateView.aspx?p=Arkitektkopia&id=a5f848e5781f440bb7baecec23cc1cf2, 2024.

[66] J. Corbin, A. Strauss, Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory, 3rd ed, SAGE Publications, Thousand Oaks, CA, 2008, https://doi.org/10.4135/9781452230153.

[67] M. Ahmad, S. Wilkins, Purposive sampling in qualitative research, a framework for the entire journey, Qual. Quant. 59 (2025) 1461–1479, https://doi.org/10.1007/s11135-024-02022-5.

[68] M. Latapí, B. Davíðsdóttir, L. Jóhannsdóttir, Drivers and barriers for the large scale adoption of hydrogen fuel cells by Nordic shipping companies, Int. J. Hydrog. Energy 48 (2023) 6099–6119, https://doi.org/10.1016/j.ijhydene.2022.11.108.

[69] N. Rehmatulla, S. Parker, T. Smith, V. Stulgis, Wind technologies, opportunities and barriers to a low carbon shipping industry, Mar. Policy 75 (2017) 217–226, https://doi.org/10.1016/j.marpol.2015.12.021.

[70] United Nations Environment Programme, Emissions Gap Report 2024: No More Hot Air … Please!, UNEP, Nairobi, 2024, https://doi.org/10.59117/20.500.11822/46404.

[71] International Maritime Organization, Fourth IMO GHG Study 2020, IMO, London, UK, 2021.

[72] J. Herdzik, A. Lesnau, Decarbonization in shipping, the hopes and doubts on the way to hydrogen use, Energies 17 (4668) (2024), https://doi.org/10.3390/en17184668.

[73] A.I. Osman, et al., Life cycle assessment of hydrogen production, storage, and utilization toward sustainability, WIREs Energy Environ. 13 (2024), https://doi.org/10.1002/wene.526.

[74] F.M. Kanchiralla, et al., How do variations in ship operation impact the techno economic feasibility and environmental performance of fossil free fuels? A life cycle study, Appl. Energy 350 (121773) (2023), https://doi.org/10.1016/j.apenergy.2023.121773.

[75] F.M. Kanchiralla, S. Brynolf, E. Malmgren, J. Hansson, M. Grahn, Life cycle assessment and costing of fuels and propulsion systems in future fossil free shipping, Environ. Sci. Technol. 56 (2022) 12517–12531, https://doi.org/10.1021/acs.est.2c03016.

[76] J. Flodén, et al., Shipping in the EU emissions trading system, implications for mitigation, costs and modal split, Clim. Pol. 24 (2024) 969–987, https://doi.org/10.1080/14693062.2024.2309167.

[77] SKGS, The Swedish industry's demand for electricity up to 2035, Accessed: Jan. 14, 2026. [Online]. Available: https://skgs.org/english/aktuellt/new-report-the-swedish-industrys-demand-for-electricity-up-to-2030/, 2024.

[78] N. Emami, R. Fazeli, T.S. Tzschockel, K.J. Dillman, J. Heinonen, Stakeholder and techno economic assessment of Iceland’s green hydrogen economy, Energies 18 (1325) (2025), https://doi.org/10.3390/en18061325.

[79] Statkraft, Statkraft stops new development of green hydrogen projects, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.statkraft.com/newsroom/news-and-stories/2025/statkraft-stops-new-development-of-green-hydrogen-projects/, 2025.

[80] Hydrogen Europe, Clean Hydrogen Monitor 2025, . Accessed: Jan. 14, 2026. [Online]. Available: https://hydrogeneurope.eu/wp-content/uploads/2025/09/Clean_Hydrogen_Monitor_09-2025_DIGITAL.pdf, 2025.

[81] International Maritime Organization, IMO's Marine Environment Protection Committee adjourns discussions on the adoption of the Net Zero Framework for one year, . Accessed: Jan. 14, 2026. [Online]. Available: https://www.imo.org/en/mediacentre/pressbriefings/pages/imo-net-zero-shipping-talks-to-resume-in-2026.aspx, 2026.

[82] A. Lind, et al., in: Nordic Council of Ministers (Ed.), Nordic Stocktake: Pathways to Climate Neutrality, 2023. . Accessed: Jan. 14, 2026. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-12983.

[83] Government of Sweden, Energipolitikens långsiktiga inriktning, Prop. 2023/24: 105. Accessed: Jan. 14, 2026. [Online]. Available: https://www.regeringen.se/rattsliga-dokument/proposition/2024/03/prop.-202324105, 2024.

[84] S&P Global, "China to dominate green hydrogen market as US withdraws subsidies, report," S&P Global Energy, Accessed: Jan. 14, 2026. [Online]. Available: https://www.spglobal.com/energy/en/news-research/latest-news/electric-power/082725-china-to-dominate-green-hydrogen-market-as-us-withdraws-subsidies-report, 2025.

[85] B.K. Sovacool, et al., Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design, Energy Res. Soc. Sci. 45 (2018) 12–42, https://doi.org/10.1016/j.erss.2018.07.007.

[86] D. Cook, N. Saviolidis, B. Davíðsdóttir, L. Jóhannsdóttir, S. Ólafsson, Synergies and trade-offs in the sustainable development goals—the implications of the Icelandic tourism sector, Sustainability 11 (4223) (2019), https://doi.org/10.3390/su11154223.