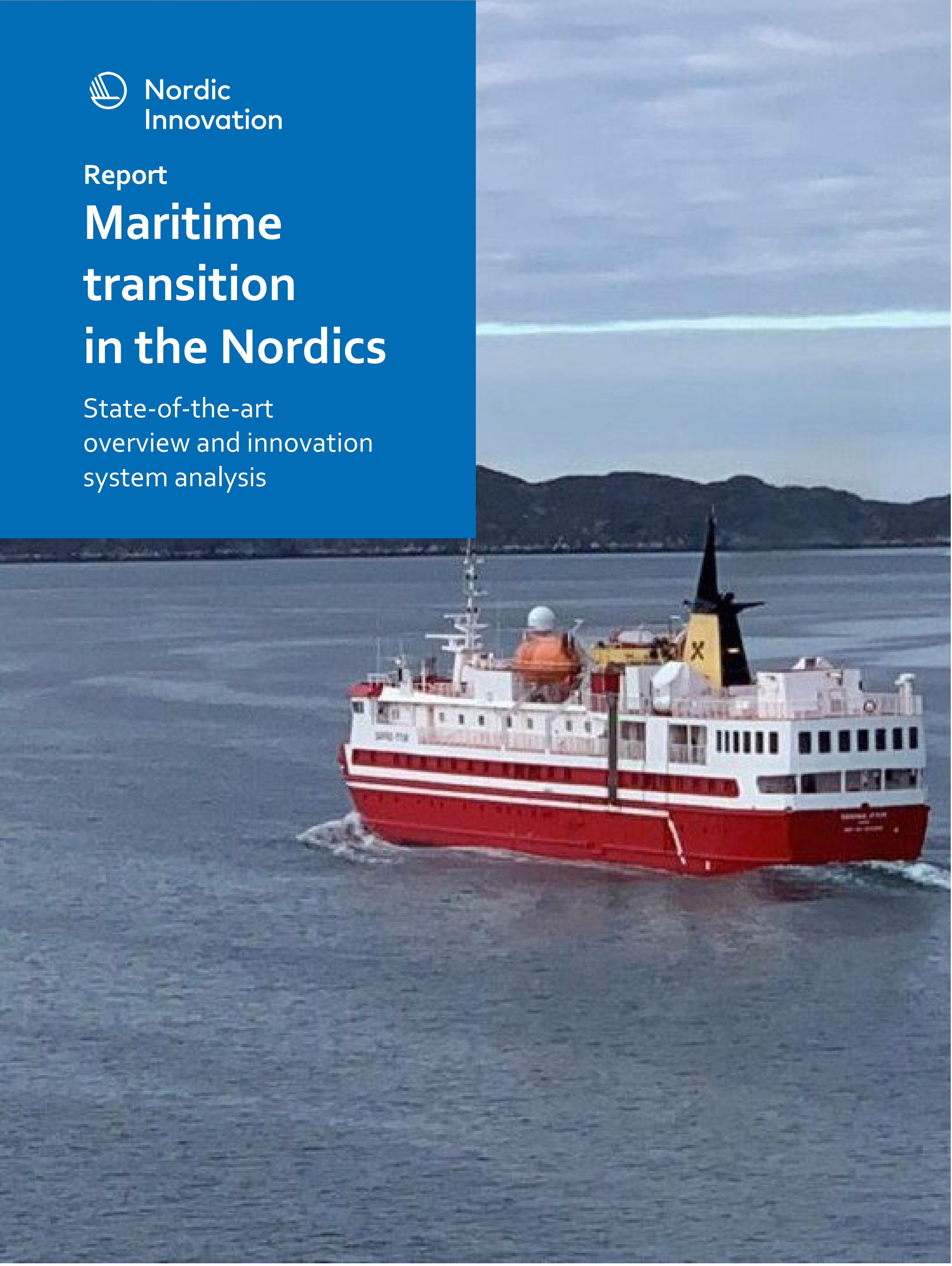
Nordic Innovation

Report

Maritime transition in the Nordics

State-of-the-art overview and innovation system analysis



Summary

To meet the decarbonisation targets for maritime transport, a sectoral energy transition is required. This report presents an overview of the maritime energy transition in the Nordics, from several perspectives. First, governmental strategies, policies, regulations and supporting schemes are reviewed, followed by a description of the Nordic ship traffic, and scenarios for the future maritime fuel mix. The recent uptakes of novel energy carriers and alternative fuels, in terms of production, infrastructure and end-use, are summarised, as well as previous studies on Nordic sectoral strongholds. Emerging markets influencing the maritime sector are touched upon, such as offshore wind, digitalisation, and carbon capture. Based on this overview, and drawing on scientific literature, Nordic strongholds were assessed through a sectoral innovation systems analysis. On this basis, a set of policy recommendations is provided.

Authors

Cecilia Gabrielii, Sigrid Damman, Markus Steen, SINTEF

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Contents

1 Introduction

This report is a deliverable from the *MAREN* project, *WP2 – Nordic Strategy on Maritime Energy Transition*. The MAREN project[1], co-funded by Nordic Innovation, is a collaboration between RISE in Sweden, SINTEF and RENERGY in Norway, VASEK in Finland, the Danish Maritime, and Icelandic New Energy.

Globally, shipping accounts for a substantial share of greenhouse gas (GHG) emissions and unless new solutions are developed and implemented in the maritime sector, GHG emissions are expected to increase in the coming decades due to global economic growth and increasing trade. This also applies to the Nordic countries, with their large and important maritime sectors. Both technical and operational measures will be needed to reduce GHG emissions from shipping. Technical measures include implementation of new energy solutions such as battery-electric systems, but also end-of-pipe solutions like onboard carbon capture (OCC) systems. Operational measures include reduced speed and better use of freight capacity. However, the main measure for achieving emission reductions is fuel switching. This means phasing out the use of fossil fuels, and developing and upscaling novel solutions such as biofuels, hydrogen, ammonia, e-fuels, and electrification. Even though technically feasible, many challenges remain, including scarcity in resources and infrastructures, competition with other sectors over low- and zero-carbon fuels, and the need to develop novel energy value chains, often more or less from scratch[2].

This report provides an overview of Nordic climate strategies, governmental support schemes, polices and regulations (Section 2), the Nordic fleet and its energy use (Section 3), scenarios for the future maritime fuel mix (Section 4), recent developments on the uptake of novel energy carriers and alternative fuels, including associated infrastructure for production and distribution (Sections 4-7), and other relevant developments, for instance within digitalisation and carbon capture (Section 8). The report also summarises previous studies on Nordic strongholds (Section 9), as well as political missions and declarations (Section 10).

Based on this overview, we then (Section 11) assess 'Nordic strongholds', i.e. areas related to the maritime energy transition in which the Nordics may have comparative advantages or particularly beneficial conditions. Note that advantages are here not thought of in economic terms, but in relation to feasibility of technology development and uptake that is necessary to reduce the environmental impact from maritime transport. We draw on the scientific literature on maritime energy transitions in the Nordics and assess strongholds through a sectoral innovation systems analysis that directs attention to entrepreneurial experimentation, knowledge development, direction of search, market formation, resource mobilisation and legitimation. On this basis, we distil a set of policy recommendations (Section 12).

2 Policies and regulations for maritime energy transition

Maritime transport in the Nordics is subject to a complex set of regulations and policies at international and national level. This chapter presents some of the international conventions, followed by an overview of relevant policy developments and regulatory changes at the EU level, and finally discusses some drivers and barriers associated with policies and regulations in each of the Nordic countries.

2.1 International regulations and standards

As shipping is a truly international industry, decisions and directions from the International Maritime Organization (IMO) play a crucial role, even though membership and adoption of standards and guidelines are voluntary. Two of the most important conventions are **MARPOL**[3] (International Convention for the Prevention of Pollution from Ships)**,** and **SOLAS**[4] (International Convention for the Safety of Life at Sea). MARPOL aims to prevent pollution of the marine environment by ships from operational or accidental causes and frames a set of more specific guidelines and regulations to limit sea and air pollution.

SOLAS lays out rules for the safe operation of ships, including design and construction, working environment, operational and environmental safety, and protective security measures. It frames several codes, such as the **IGF Code**[5] (International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels). The IGF code was originally developed for liquefied natural gas (LNG) but opens for other low-flashpoint fuels through the *"Alternative Design Process"*, which, however, requires comprehensive technical, risk and environmental assessment. Work is underway to provide interim guidelines for other IGF-related fuels and technologies. For methyl/ethyl alcohol and fuel cells, such guidelines are already adopted, while for hydrogen (H_2) and ammonia (NH_3) there are <u>draft</u> interim guidelines available[6], expected to be finalised in 2023/2024. Thus, regulatory barriers remain, both for H_2 and NH_3.

IMO is working towards the 2030 Agenda for Sustainable Development but has been criticised for not taking a proactive role in the maritime energy transition[7]. The *Initial IMO GHG strategy* was not adopted until 2018. However, in 2023, the revised **Strategy on Reduction of GHG Emissions from Ships**[8] was launched. This includes an enhanced ambition to reach net-zero GHG emissions close to 2050, a commitment to ensure an uptake of zero and near-zero GHG fuels by 2030, and indicative checkpoints to reach net-zero (20-30% reduction in GHG emissions by 2030, and 70-80% by 2040). The revised strategy envisages an average reduction in carbon intensity by at least 40% by 2030. Zero or near-zero technologies are to represent at least 5%, but striving for 10%, of the energy used by international shipping by 2030.

A basket of measures to deliver on these targets is to be developed. So far, the main measures include[9]:

- *EEDI (Energy Efficient Design Index)*, a technical measure requiring a minimum energy efficiency level per capacity mile for different ship types and size segments. It is mandatory for new ships, and the requirements in terms of CO_2 reduction levels will be tightening every five years.
- *The SEEMP (Ship Energy Efficiency Management Plan)*, a mandatory operational measure for shipping companies to manage ship and fleet efficiency performance over time, for example by using the EEOI (Energy Efficiency Operational Indicator).
- *EEXI (Energy Efficiency Existing Ship Index)*, a one-time technical design measure aiming to reduce GHG emissions. From 2023, practically all existing ships must fall below a certain limit of CO_2 emissions per cargo capacity. Compliance can be achieved through reduction of engine power (slow steaming) and/or retrofitting clean technologies (batteries, wind, low-emission fuels).
- *Carbon Intensity Indicator (CII)* in force from 2023, applies to all cargo, RoPax and cruise vessels above 5,000 gross tonnage (GT) that are trading internationally. CII is a rating scheme addressing how efficiently ships transport goods or passengers, in terms of grams of CO_2 emitted per cargo-carrying capacity and nautical mile. Rating thresholds will be tightened towards 2030.

Still, most of the instruments under IMO regulate air pollution rather than GHG emissions, and as of late 2023, there are no economic instruments, nor instruments that aim specifically for implementation of alternative propulsion technologies. A recent study[7] argues that this is due to limited capacity in IMO to govern innovation and emerging technologies, as well as uncertainty around IMO's regulatory mandate, and lack of political consensus. In a Nordic survey carried out by MAREN in 2023, 24% of the respondents considered whether IMO's climate gas reduction targets realistically can be met as an "open question", while 33% saw it as quite unrealistic, and 10% saw it as very unrealistic.

2.2 EU policies and regulations

The **EU's Fit for 55 package** provides a "basket of measures" to address emissions from transport while maintaining a level playing field. A central element is reform of the **EU emissions trading system (ETS)**[10] towards more ambitious reduction goals (-62% by 2030, compared to 2005), and extension to new sectors, including maritime transport, where ETS will be gradually introduced between 2024 and 2026. The ETS will apply to ships above 5,000 GT regardless of flag, albeit with certain exemptions, e.g. for naval and non-commercial public vessels and fishing vessels, and the price per quota will be increased in the years to come.

The revised **Energy Taxation Directive (ETD)**[11] provides a new structure of tax rates, based on real energy content and environmental performances of fuel and electricity. The revised ETD will apply to all fishing, cargo, and passenger vessels. Conventional fossil fuels and non-sustainable biofuels will be subject to the highest minimum rate, which also serves as a reference rate for the other categories. The next category of rates (two thirds of the reference rate) applies to fuels such as LNG and non-renewable fuels of non-biological origin, however only for a 10-year transitional period. The following category is sustainable biofuels, to which half of the reference rate applies. The lowest minimum rate applies to electricity, advanced sustainable biofuels and biogas, and renewable fuels of non-biological origin such as renewable H_2. Low-carbon H_2 and related fuels will also benefit from the same rate for a transitional period of 10 years.[12]

The **FuelEU Maritime**[13] initiative addresses market barriers for sustainable alternative shipping fuels, as well as the uncertainty about which technical options are market ready. It imposes increasingly stringent limits on GHG emissions of ships arriving at, staying at, or departing from EU ports from 2025, and an obligation on EU ports to become carbon neutral. From 1 January 2030, ships in EU ports shall use only onshore power supply (OPS) to cover their energy needs while at quay, unless they already operate solely with zero-emission energy solutions. The initiative applies to commercial vessels over 5,000 GT, except fishing ships.

Annual average carbon intensity must decrease by 2% in 2025 and by 6% in 2030 and then further in 5-year periods towards 2050, when carbon intensity should be 75% compared to 2020. The responsibility for compliance is placed on the shipping company. The impact is however disputed[14]. A study by the European Community Shipowners' Associations[15] found that the initiative might indirectly promote biofuels instead of developing more sustainable fuels. Also, requirements for the next 20 years are considered rather weak, implying a risk that the initiative may stimulate uptake of LNG instead of other, more sustainable fuels.

The **Regulation on the Deployment of Alternative Fuels Infrastructure (AFI)**[16] is complementary to FuelEU Maritime, aiming to ensure sufficient supply of onshore power, as well as supply and accommodate the demand for decarbonised fuels. TEN-T ports and other larger ports are required to have infrastructure for OPS to passenger ships and containerships >5,000 GT by the end of 2030. Moreover, a core network of refuelling points for LNG should be available by 2025. The regulation does not set any specific targets for H_2 bunkering facilities, but states that mandatory deployment targets should ensure a sufficiently dense network of H_2 refuelling points to allow for the seamless travel of H_2 vehicles in the EU. Technical specifications for interoperability of recharging and refuelling points should be provided, and funding will be made available under a new facility: the *Alternative Fuels Infrastructure Facility (AFIF)*.

Moreover, the **RePowerEU**[17], by boosting renewable energy, H_2 and methane, as well as introducing the "H_2 Accelerator", is influencing the expectations and framework conditions for alternative fuels. The proposed revision of the **Renewable Energy Directive** (RED III)[18] reinforces the regulatory framework for renewable energy in transport, including a combined sub-target of 5.5% for advanced biofuels and renewable fuels of non-biological origin, with a minimum level of 1% for renewable fuels of non-biological origin.

In addition, the **Guidelines on State aid to Maritime Transport** will be revised, to allow sufficient funding (such as for OPS), while avoiding distortion of competition[19]. Also, the EU **Taxonomy Regulation** includes quite comprehensive technical screening criteria for maritime transport[20]. While the requirements in the technical screening criteria may result in more limited access to green capital, alignment with the criteria may also represent a potential opportunity for companies with activities recognized as "green". Overall, the taxonomy is likely to accelerate the sector's uptake of zero-emission solutions.

2.3 Policies and key instruments at the national level

2.3.1 Norway

The targets stated in **Norway's Climate Change Act**[21] include GHG emission reductions of at least 55% by 2030 (compared to 1990) and 90-95% by 2050, as well as achievement of climate neutrality by 2030. The government's specific target for domestic shipping is a 50% cut by 2030, compared to 2005. This comes with an estimate that 700 low-emission and 400 zero-emission ships will be required. The Norwegian Shipowners Association have their own goals, e.g. to only order zero-emission ships from 2030, a climate-neutral fleet in 2050, and striving for a global ban in 2050 on fuels that are not carbon-neutral[22].

The national **Action Plan for Green Shipping**[23] provides both general measures and specific measures for different vessel categories. These are related to the ambition to transfer 30% of freight >300 km from road to sea by 2030, and to increase export from the maritime sector. Moreover, Norway aims to be a driving force in strengthening IMO's emission reduction efforts. Examples of measures include:

- Low- and zero-emission requirements in procurement processes of ferries, high-speed vessel service, aquaculture and off-shore, where feasible.
- Governmental support for R&D&I, e.g. through Enova and the Green Shipping Programme.
- Governmental support for OPS and charging infrastructure, bunkering facilities of alternative fuels.
- Consider a biofuel quota obligation for advanced biodiesel and biogas for shipping.
- Increase the carbon tax rate by 5% per year.
- Establish a national plan for port development and/or alternative fuels infrastructure.

In the **National Transport Plan (NTP)**[24] for 2022-2033, 33 billion NOK are set aside for coastal management and 3 billion are earmarked for projects involving actors across sectors in public-private collaboration for more sustainable transport solutions. The plan also includes specific measures to strengthen short sea freight transport, and a new national port plan. Other elements are an incentive scheme for short sea shipping, the continuation of a condemnation scheme and lending scheme for short sea and fishing vessels, and grant support for investment in efficient and environment-friendly ports.

Priorities in the White Paper **Greener and smarter maritime industry** (Meld. St. 10(20-21))[25] include development of environment-friendly shipping, digitalisation of the maritime sector, and Norwegian maritime competence. While noting many of the same points as the policy documents mentioned above, the importance of the **NOx Fund** [26]is also emphasized. The NOx Fund is a voluntary agreement whereby industry can pay a fee to a fund that is managed and used by the industry itself to stimulate environment-friendly solutions, instead of paying state tax for NOx emissions. A large part of the NOx Fund has been used for electrification of shipping, NOx purification with catalysts, and introduction of LNG-fuelled ships.

The **Action plan for infrastructure for alternative fuels in transport**[27] from 2019 aims to help realise the transport sector's emission reduction targets and implement the EU Directive on alternative fuels infrastructure (AFID) in Norwegian legislation. One important objective is to facilitate timely development of charging infrastructure in all parts of the country, through a combination of public policy and market-based solutions. Enova is presented as the key instrument, although some support may also be granted by counties and municipalities. If the targets of the NTP 2018-2029 are used as a basis, the Norwegian Water Resources and Energy Directorate suggests a total electricity demand from transport in the range of 13 to 15 TWh by 2040[28]. The **Harbours and Fairways Act**[29] enables municipalities and ports to stimulate the use of shore power through environmental differentiated fees and charges. Reduced electricity tax for ships in enterprise is an important tool to facilitate more use of shore power and can contribute in fully, or partly, electric vessels. However, the current high prices on electricity can be negative for the development.

As regards H_2, the action plan for alternative fuel infrastructure, mentioned above, emphasizes the need to see synergies between use of H_2 across different sectors and transport segments, and that Enova is ready to provide support for refuelling/bunkering stations as and when demand increases. The **Government's H_2 Strategy** defines H_2 as a priority area. For example, the **White paper on energy** (Meld. St. 36 (2020-2021))[30] stated that, by 2025, the government aims to facilitate five H_2 hubs for maritime transport. This was followed up in 2022, when Enova granted support to five such projects. The grants amount to a total of 669 million NOK, and when realised the projects will be able to provide fuel for 35-40 ships. Importantly, the H_2 hub grants were accompanied by funding for seven H_2- and NH_3-fuelled vessels, at a total of 451 million NOK. The present government's platform underscores the intent to build a coherent value chain for H_2 energy, and to set a goal for annual production of H_2 by 2030. The government also states the ambition to significantly increase the infrastructure for climate-friendly heavy transport and ships by 2025, with charging and filling stations for renewable fuels, such as H_2, NH_3, and biofuels, along the coast.

A recent report on H_2 value chains, commissioned by the Ministry for Petroleum and Energy[31], recommends an increased and expanded CO_2 pricing, to improve the predictability and economic viability of alternative technologies, as well as continued R&D support. Moreover, contracts for difference (CFD) for green H_2 production are presented as a relevant instrument, entailing a long-term commitment from the government in making green H_2 production economically viable and less risky for the actors. However, CFD for H_2 are not included in the government's recent strategy for green transition in industry ("Grønt Industriløft")[32].

2.3.2 Denmark

According to the national **Climate Act**[33], Denmark must reduce GHG emissions by 70% in 2030, compared to 1990, and become a climate-neutral society by 2050. The main measures to reach these goals include offshore energy islands, local solar farms, biogas, carbon capture and storage (CCS) and taxations[34]. The strategy on Power-to-X (PtX) and carbon capture and utilisation (CCU) includes a proposal for sustainable maritime fuels, stating that electrification should be prioritised where possible. NH_3 is associated with a considerable potential for shipping decarbonising, while H_2 is related more to industry decarbonisation. The strategy also includes a mapping of port infrastructure, looking at port readiness for the green transition.

The Danish Shipping Strategy "Towards Zero"[35] states the same targets as the Climate Act, entailing that:

- By 2030, at least 5% of the Danish-operated fleet is capable of running on well-to-wake net zero-emission fuels such as green H_2, green NH_3, green methanol, and advanced biofuels.
- All new-builds ordered by Danish shipowners from 2030 are to be made ready for net zero-emission fuels or other zero-emission means of propulsion.
- The Danish shipping sector is actively engaged in offshore wind, the development of transport and storage solutions for captured carbon, as well as utilisation of CO_2 in PtX over time.

The **Government's report on deployment of alternative fuels infrastructure**[36], emphasizes the crucial role of CO_2 taxes and differentiated energy taxes on fuels. When it comes to maritime transport, it is noted that all Danish ports offer OPS to ships requiring a limited power supply. However, it is difficult to make a business case for OPS to ships having substantial power needs, such as cruise ships, implying that such installations are subject to uncertainty. Still, an increase towards 2030 is expected, both for OPS and LNG.

2.3.3 Sweden

As stated in the **Swedish Climate Change Act**[37], the long-term target is zero net GHG emissions by 2045 at the latest, and negative net emissions after 2045. For domestic shipping the goal is a reduction of 70% by 2030, and zero net emissions by 2045. The Swedish Shipping Association[38] states that to realise the emission goals, the Government must take the following actions:

- Increase the production rate of renewable power and fuels.
- Increase financial support to R&I in general, and for shipping particularly.
- Promote front-runners in their efforts to use alternative fuels.
- Invest the up-coming income from EUs ETS into the maritime energy transition.

Some of the current policy instruments that influence maritime transition efforts are as follows[39]:

- **Eco bonus:** Support for transfer of goods transportation – from road to shipping. This does not automatically reduce shipping's GHG emissions, but the overall emissions per tonne transported goods can be reduced if emissions from ships are lower than the corresponding transport by truck.
- **Reduction of energy tax:** Ships larger than 400 GT receive a reduction in energy tax (to 6 SEK/MWh) in regard to the shore power used by the ship in port.
- **The climate step "Klimatklivet":** Support for climate measures in shipping can be sought within the governmentally founded program "Klimatklivet".
- **Environmentally differentiated fairway fees:** Part of the Swedish Maritime Administration's fairway fee is based on an index, where CO_2 emissions are one of five parameters being assessed.
- **Environmentally differentiated port fees:** Several ports, which are often municipally owned, have introduced port charges that reward environment-friendly ships and electricity connection in port.
- **Tax and reduction obligation on fuels:** Fossil fuels for commercial shipping are not subject to tax or to reduction obligations. However, fuel for leisure boats is taxed in the same way as road traffic with energy tax, CO_2 tax and value added tax, and the fuel is subject to the reduction obligation.

Upcoming instruments, noted in the online workshop on policy and regulations organised by MAREN[40] in March 2023 include[41]:

Means to economically promote ship traffic with low emissions:

- Development of the Swedish Maritime Administration's fees
- Climate-differentiated shipping support
- Swedish carbon dioxide fund, as an alternative and supplement to a tax on fuel
- Climate requirements in an expanded eco bonus

Means that set requirements for ships' greenhouse gas emissions:

- National fuel requirements for smaller vessels
- Developed requirements for the governmental fleet

Guidance to increase knowledge of measures that reduce emissions:

- Expanded assignment to national coordinator for the sustainable transition of shipping
- "Transition program" according to the Norwegian model
- Consulting support for greener shipping according to the Norwegian model

2.3.4 Finland

Finland's **Climate Act**[42] from 2022 includes emission reduction targets of 60% by 2030, 80% by 2040 and 90-95% by 2050, all compared to the levels in 1990. In addition, Finland aims for carbon neutrality by 2035. According to the **Government Resolution on reducing GHG emissions from maritime and inland waterway transport**[43], Finland is committed to the IMO's emission reduction objectives and the EU's emission reduction targets, but apart from this there are no numeric national goals for reducing climate gas emissions from ships[44]. However, the Finnish Shipowners' Association has set an ambitious goal of being carbon neutral by the year 2050. The resolution document[43] emphasizes that since different power sources and fuels are needed, depending on ship type and voyage length, multiple options should be developed in parallel, including LNG, liquefied biogas (LBG), drop-in biofuels, as well as methanol, H_2, NH_3 and synthetic fuels. More national research and innovation funding will be dedicated to developing such fuels, and the ship technologies required to use them in the Baltic Sea region.

Provided that Finland is allowed to apply a reduced tax rate to shore-side electricity similarly to Sweden, Denmark and Germany, OPS in commercial ports will be transferred to the lowest electricity tax category. Distribution infrastructure will be supported in line with EU's AFI Regulation. Key measures include discretionary government transfers for shipbuilding innovations that reduce GHG emissions, and an investigation of the possibility of creating a state support scheme for ship retrofits and acquisitions of new-builds that reduce GHG emissions. The potential of digital solutions to provide more energy efficient transport solutions and optimizing ports' role as sustainable transport hubs are also emphasized[45].

The **Maritime Policy Action Plan**[46] promotes the implementation of EU's maritime policy. Key priority actions include:

- Influencing GHG reduction targets and measures on maritime transport (IMO, EU, Baltic, Nordic)
- Promoting digitalisation of data flows in national and international corridors and nodes (e.g. ports)
- Making the Baltic Sea an international testbed area for autonomic maritime transport
- Promoting the prerequisites for building marine energy production, considering spatial planning
- Guaranteeing availability of future maritime energy in Finnish ports.

2.3.5 Iceland

Iceland is committed to a 55% cut in GHG emission by 2030 (compared to 2005) and aims for carbon neutrality in 2040[47]. Since the power and heating sectors already have low emissions (geothermal heating and hydropower electricity), the reduction must be achieved in only a few sectors, including transport. Important measures are taxation and CCS (carbon capture and storage). In a parliamentary resolution from 2017, the Icelandic government set a sector-specific goal to transition from 0.1% to 10% utilisation of renewable energy in the maritime sector by 2030[48].

Iceland's **Climate Action Plan 2020**[47] aims, amongst others, to permanently phase out the use of heavy fuel oil (HFO) in Iceland's territorial waters. Of the 48 actions, the following are most relevant for shipping:

- Energy transition in fisheries: biofuel, or possibly H_2, and electrification of smaller ships.
- Energy transition of ferries in regular operation and categorised as a part of the national highway system: switch to non-fossil fuelled options where technologically feasible.
- Onshore power supply: meet the ships' power demand in port by 2025, also demands >500 kW.
- Domestic renewable fuels: Evaluate which fuels are most cost-effective to produce and use in different applications and determine where more research is necessary.

In 2024 an updated Climate Action Plan will be launched. The government is also working, together with key stakeholders, on a sector-based roadmap, including the role of maritime industry vs. government[49].

3 Nordic ship traffic – a brief overview

This chapter provides an overview of Nordic ship traffic, in terms of fleet characteristics and energy use. The numbers presented below are taken from DNV's *AIS Analysis of Nordic Ship Traffic*[50], performed within the project *Nordic Roadmap - Future Fuels for Shipping*[51], financed by Nordic Innovation.

3.1 Characteristics of the Nordic fleet

Nordic ship traffic is defined as ships with at least one port call in a Nordic country during the year. In 2019 it represents about 8,900 unique vessels (having an IMO number) with a total fuel consumption of 8.6 Mtoe (million tonnes of oil equivalents), corresponding to 26.8 million tonnes of CO_2 emissions. Figure 1 (right bar) illustrates the share of CO_2 emissions (energy use) for different ship types, showing that over 50% is related to cargo and bulk ships, 25% to passenger and cruise ships, 15% to workboats, and 7% to fishing vessels.

Figure 1 also presents other characteristics of the Nordic ship traffic. For example, it shows that the number of vessels is dominated by cargo and bulk ships, while the number of voyages and the sailed distance is dominated by passenger ships and work/service boats, respectively.

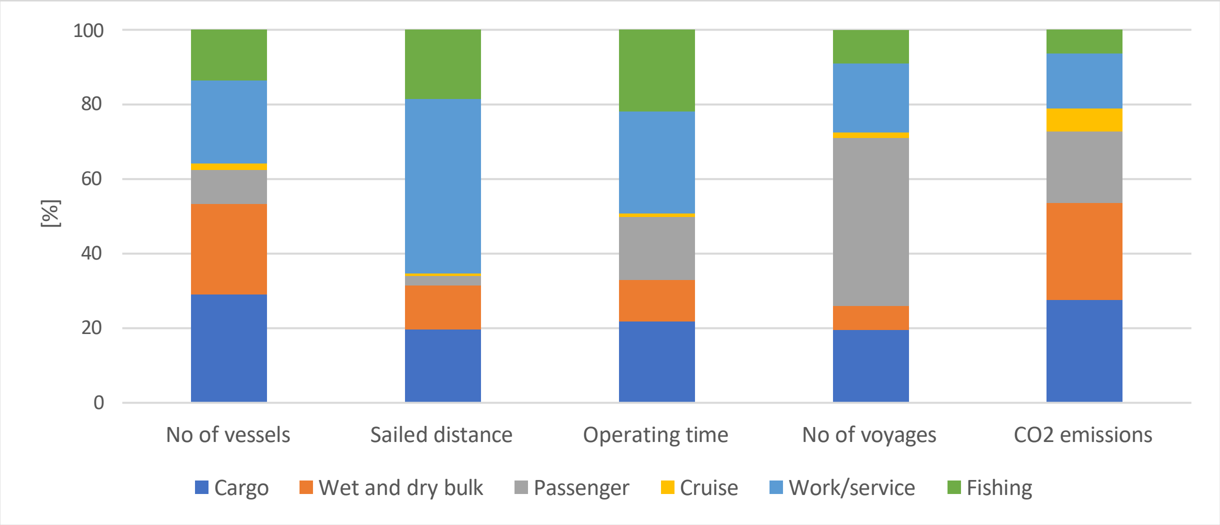

Figure 1: Characteristics of Nordic ship traffic, based on data from DNV (2022)[50]

Nordic ships traffic can be divided into three categories:

- Domestic Nordic traffic: voyages between ports in the same Nordic country
- Intra-Nordic traffic: voyages between ports in two different Nordic countries
- Nordic international traffic: voyages to/from a Nordic port from/to a port in a non-Nordic country

Figure 2 shows the share of energy usage for the three categories, and the share of different ship types in each category. The Nordic International traffic represents 58% of the total energy usage, while 32% is related to domestic traffic and only 10% to intra-Nordic traffic.

- The Nordic international traffic's energy use is clearly dominated by cargo and bulk ships. About 75% is related to traffic within Europe, and mostly in Northern Europe.
- For domestic traffic, the energy use is dominated by service/supply boats (mainly in the aquaculture and offshore sector) and passenger ships. The fishing fleet also has a relatively large energy use.
- The intra-Nordic traffic's energy use is more evenly distributed on several ship types, but with passenger ships (RoPax) having the largest share.

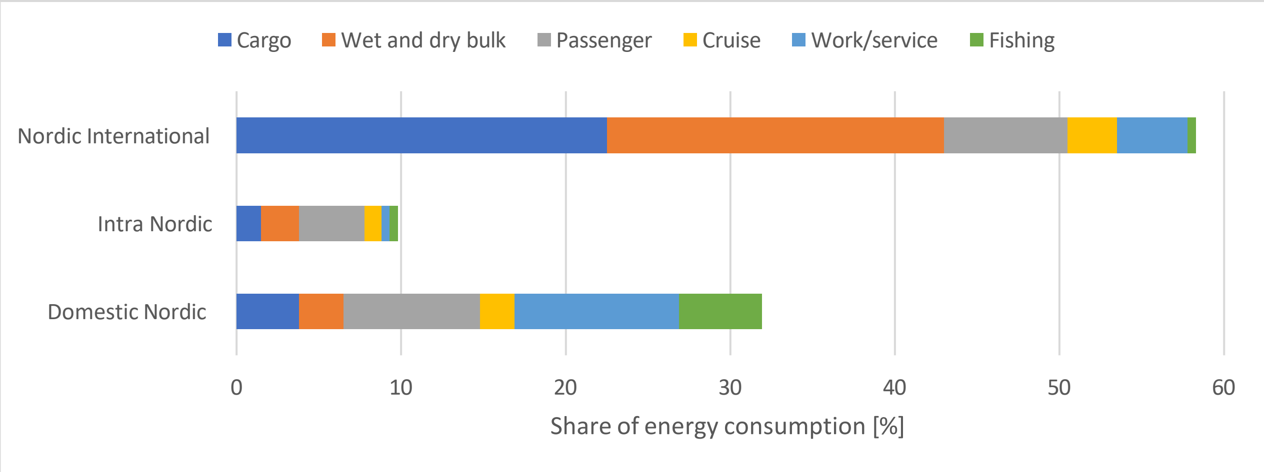

Figure 2: Share of energy use for domestic, intra- and international Nordic traffic, and for different ship segments, based on data from DNV (2022)[50]

3.2 The ship traffic in each Nordic country

In this section, an overview of the energy use from ship traffic in each Nordic country is presented, also based on DNV's AIS report. Figure 3 shows the five countries' share of energy use for all Nordic traffic categories. As seen, Norway's ship traffic represents 45%, followed by a rather equal share for Sweden, Denmark and Finland, while Iceland's share is only 4%.

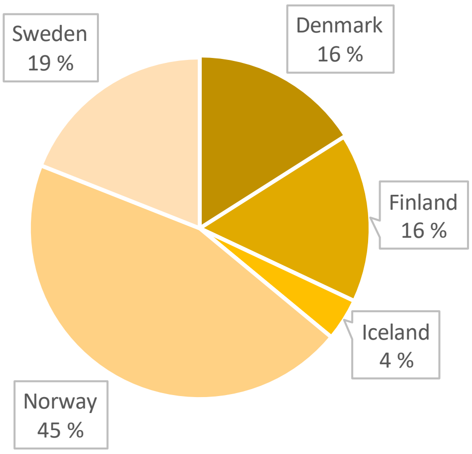

Figure 3: Each country's share of energy use in all Nordic ship traffic, based on data from DNV (2022)[50]

Figure 4 compares the share of energy use between domestic, intra-Nordic and Nordic-international traffic for each country. As seen, domestic traffic dominates in Norway, Iceland and Denmark, while international traffic dominates in Sweden and Finland. Looking at the share of energy use for different ship types in the various countries (Figure 5), Denmark and Norway have the most varied shipping sector. In Sweden and Finland, cargo, bulk and passenger vessels represent 90% of total energy use. For Iceland, the fishing fleet uses more than one third of the total energy use, and cruise vessels also have a relatively large share (20%).

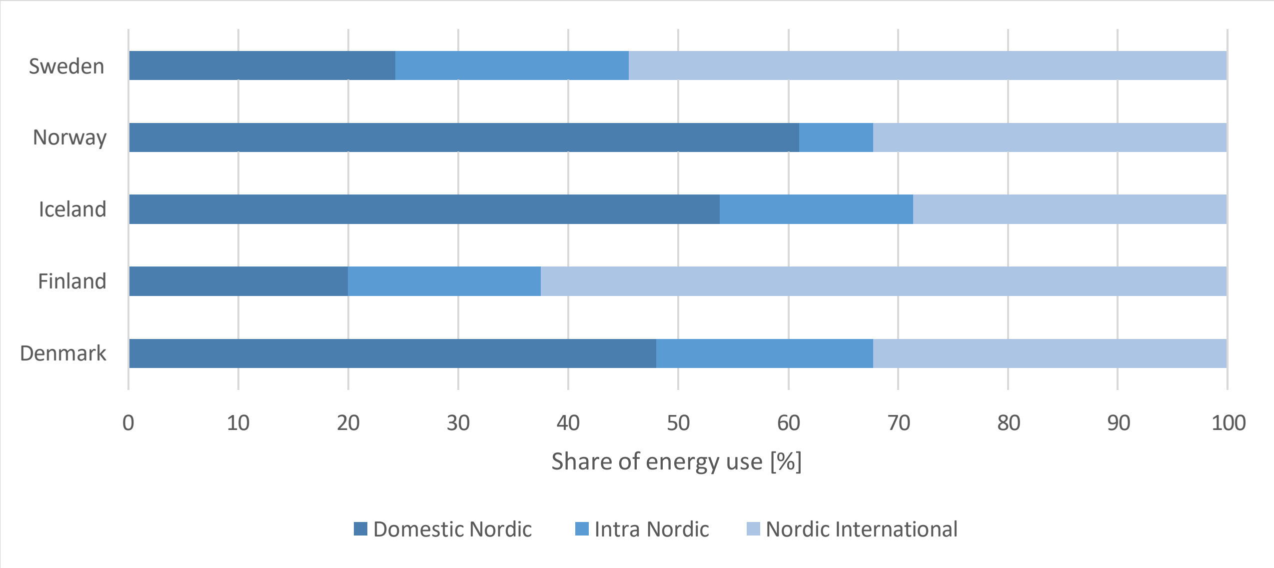

Figure 4: Share of energy use in domestic, intra-Nordic and Nordic-international traffic, for each country, based on data from DNV (2022)[50]

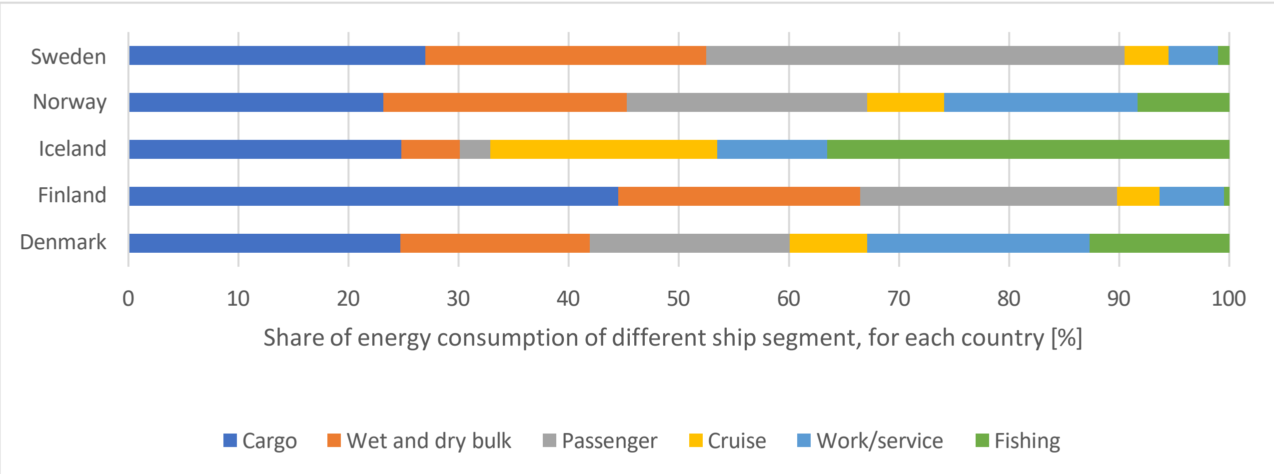

Figure 5: Share of energy use by ship segment, for each country, based on data from DNV (2022)[50]

4 Future maritime fuel mix

4.1 Global scenarios

The large number of plausible maritime energy transition pathways is driving complexity. Several fuels can be applied, with various onboard technology options. While industry actions and policies can narrow the fuel pathways, several solutions are likely to co-exist. Numerous scenarios for the future maritime fuel mix are published[52], mostly on a global level. This chapter summarises some of the most cited ones.

Note that all scenarios presented here were published before the adoption of IMO's revised GHG strategy[53], in which reduction targets for international shipping were significantly strengthened. The revised strategy also includes a target for 2030, on 5% uptake of zero or near-zero emission fuels and/or energy sources.

DNV Energy Transition Outlook 2023[54], Maritime Forecast 2050[55]

- Even though fleet and ship optimisation, wind-assisted propulsion, OCCS, and energy efficiency enhancements will contribute to emission reductions, the main decarbonisation will be realised by switching to low- and zero-carbon fuels, estimated to 84% of the fuel mix by 2050.
- NH_3 is projected the largest share (36%), followed by biofuel (25%) and e-fuels (19%).
- The role of electricity is anticipated to be minimal at 4%.
- The fuel mix depends on many factors, e.g. availability of advanced biofuels and renewable H_2.

IEA Net Zero by 2050[56]

- Ships' long lifetime contributes to oil still constituting 15% of the shipping fuel demand in 2050.
- Drop-in fuel solutions will enhance decarbonisation since existing ships and engines can be used.
- By 2050, NH_3 meets around 45% of demand, while biofuels and H_2 each meet 20%.
- Electricity plays a minor role, focused on meeting the demand for small ships and cruise ferries.

BP Energy outlook 2023[57]

- In the two scenarios "Net Zero" and "Accelerated", the share of fossil oil fuel is still 10-40% in 2050.
- The initial reduction in fossil oil use is mostly replaced by LNG with a potential for swapping to LBG.
- The gradual transition towards decarbonisation is led by H_2-based fuels (NH_3 and methanol)
- The share of H_2-derived fuels is 3-8% in 2030 and reaches 10-55% in 2050.
- Biofuels represent 5-15% of the fuel mix in 2030 and 15-20% in 2050.

IRENA 1.5 scenario 2050[58]

- Diverse fuel mix with NH_3, H_2 and methanol comprising more than 60% in 2050.
- Biofuels play a limited role in the shipping sector, with only a 10% share by 2050.
- The shipping sector still emits GHGs in 2050 – but reaches an 80% reduction compared to 2018.

Shell Sky 1.5[59]

- In 2100, shipping still emits GHG, due to a large share of liquid hydrocarbon fuels.
- Gaseous hydrocarbons and H_2 only emerge very gradually.
- By 2100, shipping has a share of only 1-4% of the annual global H_2 consumption.

Getting to Zero Coalition[60]

- Scalable zero-emission fuels (SZEF) are introduced in 2026, a step change in growth towards 2031.
- LNG use expands until 2026, then remains constant with only a modest share of the fuel mix.
- The expansion of SZEFs from 2020 to 2040 follows an S-curve typical for technology transitions.

4.2 EU scenario

The European Commission[61] presented a fuel mix scenario for the EU shipping sector in 2030 and 2050, in connection with their consequence analysis of the FuelEU Maritime proposal.

- By 2030, the share of renewable fuels is only 9%, primarily as biodiesel, but 1% each for bio-LNG and electricity (not including OPS).
- By 2050, the share of renewables is almost 90%. Biodiesel and bio-LNG constitute 48% and 17%, respectively, e-fuels represent 18%, while H_2 and NH_3 together have a share of 5%.

4.3 Nordic scenarios

In DNV's analysis of Nordic ship traffic[50], the feasibility of batteries and potentially zero-carbon fuels (including H_2, NH_3, and methanol) for Nordic ship traffic was assessed, showing that:

- Around 3% of the total energy use of Nordic ship traffic may be covered by battery electric ships, primarily for domestic operation but also some intra-Nordic traffic.
- Close to 40% of the Nordic ship traffic has a *theoretical* potential to be covered by H_2, mainly due to the Nordic regions and northern continental Europe being geographically close.
- The remaining fleet (60%) requires higher energy density fuels, e.g. methanol, NH_3 and biofuels.
- Theoretically, NH_3 or methanol can cover over 80% of the Nordic ship traffic's energy use.

Since fleet characteristics vary between the Nordic countries (see 3.2), the feasibility for alternative fuels also differs. In Figure 6, the potential share of fuel usage in the Nordic ship traffic that could be covered by H_2 (left) or NH_3/methanol (right) are shown for each country, divided on the three ship traffic categories.

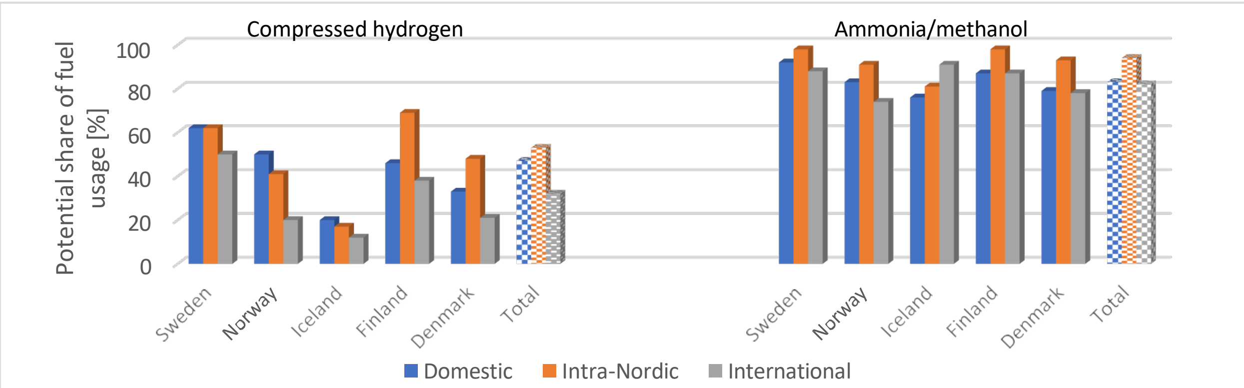

Figure 6: Share of each country's fuel use in Nordic Ship traffic that potentially could be covered by H_2 (left) or NH_3/methanol (right), based on data from DNV (2022)[50]

Within the Nordic Energy Research project *Nordic Clean Energy Scenarios*[62], potential long-term pathways to reach carbon neutrality in 2050 were suggested, by modelling three main scenarios:

- Carbon Neutral Nordic: least-cost pathway, applying current national strategies and targets.
- Nordic Powerhouse: providing Europe with renewable power/fuels, and carbon storage.
- Climate Neutral Behaviour: adopting additional energy and material efficiency measures.

The following suggestions, related to the shipping sector, are valid for all three scenarios:

- Fossil fuel use needs to decrease from almost 100% in 2020 to around 10% in 2050.
- In both national and global shipping, fossil fuels are replaced by PtX fuels, biofuels and electricity.
- During the 2030s, biofuels remain a major renewable alternative in shipping.
- Synthetic natural gas and H_2 dominate fuel use in 2050. Most synthetic fuels are based on green H_2, but some are derived from bioenergy, and in some cases combined with CCS.

4.4 National scenarios

4.4.1 Norway

For Norway, there are several reports with estimates of the maritime fuel mix in 2030 and 2050, e.g. DNV's *Energy Transition Norway*[63] and the Environment Agency's *Zero emission scenarios for 2050*[64]. Compared to global and Nordic scenarios, there is generally a larger share of NH_3 (20-50% in 2050), and a somewhat larger share of H_2, while the uptake of biofuels is relatively low. Each year, the Norwegian Shipowners Association[65] presents a survey on how to reach their climate goals in 2050. When comparing results for 2023 with previous years, electric-hybrid propulsion remains the preferred option. However, in terms of alternative fuels, NH_3 has made a strong entrance, the belief in e-fuels has increased, while the interest in H_2 and LNG has declined. Shipowners still consider high investment costs as the main barrier for fuel switch, but the lack of fuel availability is now considered a larger barrier than the lack of technology.

4.4.2 Denmark

IDA's Climate Response 2045[66] is a vision on how the energy and transport sector can achieve 70% reduction in GHG emissions by 2030 and climate neutrality by 2045. Designing a pathway for decarbonised transport sector is complex, especially due to Denmark's high share of international aviation and maritime transport, significantly increasing the demand for bio- and e-fuels. Implications for the maritime sector include:

- Electrification of all domestic and 10% of international ferry transport in 2045.
- Use of NH_3 and e-fuels (methanol) where electrification (i.e. batteries) is unfeasible.
- In addition to e-methanol, the production of NH_3 could be increased significantly from 2030.
- A PtX strategy shall ensure that Denmark is in front of developing e-fuels for maritime transport.

4.4.3 Sweden

A report by Sweco[67] shows predictions of the fuel mix in domestic shipping towards 70% emission reduction by 2030, and zero-emission by 2045. The total energy use towards 2045 is assumed constant, based on equalization of increased ship transport and energy efficiency. Three scenarios are presented, with various levels of electrification of the transport sector. The main results for maritime transport include:

- In 2030, electricity use is 1% in all scenarios, while in 2045 it is 3%, 5% and 11%, respectively.
- The use of LNG and LBG increases from 10% in 2021 to 20% in 2045, with LNG dominating the increase towards 2030, which is then gradually replaced by LBG.
- E-fuels, primarily methanol, but also NH_3, are expected to enter the fuel mix after 2030 and accelerate towards a share of 40-50% in 2045, depending on the electrification level.
- H_2 is expected to be introduced after 2030, and increases towards 10% in 2045.
- The use of liquid biofuel increases from 2% in 2021 towards 8% in 2030 and 17% in 2045.

4.4.4 Finland

Today, about one fifth of Finland's transport sector is based on renewable energy, mostly represented by biofuels. To achieve the national goal of carbon neutrality in 2035[68], the role of liquid biofuels, biogas and new H_2-based e-fuels is expected to be important in heavy road, maritime and air transport. Plans have been set up to become "Europe's leader in the H_2 economy across the entire value chain", including a target for e-fuels derived from green H_2 to make up 3% of the country's transport fuel by 2030[69].

4.4.5 Iceland

The DNV report on *Pathways for decarbonising the Icelandic maritime sector*[70] presents a scenario towards using 10% renewable energy in 2030 and becoming fossil-free in 2050. The following indications are given:

- In the beginning, the major share of carbon-neutral fuel is drop-in fuel (liquid biofuels and e-diesel).
- Around 2040, the e-fuels become dominating, especially methanol.
- A CO_2 tax, and a 50% investment support, will significantly increase the share of NH_3 and H_2.

5 Electrification of the maritime sector

The Nordics, especially Norway, are at the forefront of offering onshore power supply (OPS) and have a rapidly increasing number of hybrid and fully electrified ships. The project "On Shore Power Supply in the Nordic Region"[71], financed by Nordic Innovation, provides a situation analysis of the OPS infrastructure.

5.1 Shore power

The first commercial OPS facility was implemented in Sweden (Gothenburg). Today, Norway has the largest number of facilities, mostly for domestic ferries, but also Europe's first and largest OPS plants for cruise ships (Kristiansand and Bergen, respectively). The EU AFI regulation implies future requirements for OPS[16]:

- Container and passenger ships over 5000 GT are obliged to use OPS, if available, for all electricity needs in major EU ports as of 2030, and in all ports as of 2035.
- **Ports** with at least 50 port calls of such passenger vessels, or 100 port calls by such container vessels, must provide OPS by 2030.

5.1.1 Norway

ENOVA has since 2015 supported 193 OPS projects, and the number of OPS plants is today almost 200, compared to 92 in 2019[72]. In 2023, the Enova support scheme was withdrawn, as was the one for onboard battery installation. However, a new support program on transport electrification will be launched in 2024. At the Nordic Workshop on Shore Connections[73], arranged by NEK and MAREN, the Norwegian Speed boat association expressed a need for governmental support to develop standardised fast charging facilities for all types of passenger ships. In light of the AFI regulation, the Coastal Administration reported on 10 ports with existing or planned OPS to cruise ships, and that yet another 10 will be obliged to offer OPS.

Despite the high availability of OPS, utilisation is in many instances low. There are mainly three reasons for this: many ships are still not being prepared for OPS, the use of available power is not optimised, and uncertainties exist around technical solutions and costs. However, there are many ongoing activities on standardisation and technological development, e.g. automated solutions to ensure safe and efficient operation of ultra-fast Megawatt charging systems (MCS)[73]. With regards to costs, a tool for comparing the cost of OPS vs. onboard power generation was developed in the *ElMar* project[74].

5.1.2 Denmark

Most Danish ports offer OPS to some extent, but primarily for small ships. Many ports are interested in expanding OPS to more ships and ship types[71]. There are several planned facilities, mostly based on access to wind power. Some of the largest existing facilities are in Esbjerg and Grenaa for offshore construction vessels, in Copenhagen for cruise ferries, and in Skagen for pelagic fishing vessels. In 2023, Aarhus opened Denmark's first OPS for cruise ships. To promote electrification of ships, it is argued that today's reduced tax rate on electricity from OPS should be expanded to include ships with electrical propulsion.

5.1.3 Finland

Most Finnish ports that offer high-voltage OPS were established for specific shipping lines, mostly RoPax ferries, as in the ports of Helsinki, Oulu, Kemi and Mariehamn. In Helsinki, additional OPS facilities for RoPax ferries are planned, but also for cruise and cargo ships[71]. The Finnish Port Association asks for a governmental programme on large-scale electrification of ports. Although EU's AFI regulation may only apply to four Finnish ports, another twenty ports expect their customers to require OPS within a few years, especially in the container and cruise sectors[75].

5.1.4 Iceland

In Iceland, the ports' focus for OPS has been on low voltage infrastructure, supplying their home fleet (fishing ships and other small ships). Ports with OPS facilities above 500 kW are limited but increasing.

Reykjavík offers OPS to cruise and container vessels, Hafnafjordur offers 1 MW OPS (primarily used by container ships), Seyðisfjörður has a 1.3 MW installation for Smyrilline, and a few others are in the planning phase. In 2019, charging infrastructure for Iceland's first hybrid-electric ferry was set up in Vestmanna Islands[71].

While Associated Icelandic Ports has several plans for OPS to cargo and cruise ships, the power grid capacity is a challenge, especially for large cruise ships visiting small villages and having a high short-time power demand. One solution could be to supply reserve power, possibly with H_2, to offset volatile demand. There is also a need for governmental support for OPS and charging infrastructure. Legislation on Environmental Port Index (EPI) is in progress, which would benefit ships using OPS[47].

5.1.5 Sweden

Today, nine larger Swedish ports offer OPS: Stockholm, Gothenburg, Visby, Helsingborg, Karlskrona, Ystad, Trelleborg, Piteå and Luleå, and several are preparing for it. Some ports have local power production, such as Trelleborg where solar parks and wind turbines supply the port's electric needs, including OPS and vehicle charging. The ship segments currently utilising OPS in Swedish ports include ferries, RoPax, RoRo, bulk carriers, workboats and recreational crafts. Investment support is mainly given through "The Climate Step" a funding scheme by the Swedish Environmental Protection Agency[73].

In 2023, the Port of Stockholm will open Sweden's first OPS for cruise ships. The port collaborates with the ports of Copenhagen, Århus and Helsinki on a common international OPS standard for cruise ships[76]. Through the project *Green Cable*[77], the Port of Gothenburg aims to become the world's first port providing OPS to tankers berthed at an energy terminal, and also to set a new global standard for OPS to tankers berthed in a hazardous environment.

Regarding battery charging infrastructure, the project *Seacharging*[78] analysed the current situation and need for standardisation, by performing stakeholder interviews to understand drivers and barriers.

5.1.6 Heat supply in port

Connecting to OPS eliminates the ship's need to run diesel engines for covering the electric power demand during port stays. However, most ships, especially cruise and certain tanker vessels, also have a significant heating demand in port, traditionally covered by waste heat from diesel engines and oil-fired boilers. Thus, even though OPS reduces emissions from diesel engines, it might actually increase boiler emissions. One obvious solution is to use electric boilers, but the increase in OPS capacity must then be considered.

Another potential option is onshore heat supply[79]. Since 2014, a Stena Line RoPax ferry, operating between Sweden and Denmark, connects to the district heating network while at berth in Gothenburg[80]. Together with Norsk Fjernvarme, the port of Oslo evaluated district heating supply to ships. One identified barrier is the steam-based heating systems that are conventionally installed on board[79]. However, today, many ships are built with systems based on hot water, which make heat supply from port more feasible. Several Icelandic ports offer ship connection for hot water supply. While the service has not been utilised fully, it is regularly used by the Icelandic Coast Guard and pilot boats[81].

5.2 Battery-electric vessels

Maritime Battery Forum[82] reports on approx. 800 vessels being registered as fully electric or battery-hybrid, globally. The total installed battery capacity is 300 MWh and is expected to double in 2024. Installations on ferries and offshore vessels dominate but with an increased interest from other sectors, including "deep sea". Norwegian ships represent a significant part of the installations, and the main global battery supplier is the Norwegian-based Corvus Energy. In Norway, the electrification of other segments than ferries was realized through ENOVA's support scheme established in 2020, however, withdrawn in 2023. Since 2021, batteries are found on 263 aquaculture and 39 fishing vessels, and 12 offshore ships[83].

The world's first fully electric fast ferry, built in accordance with IMO's HSC (High Speed Craft) Code, was demonstrated through the EU project *TRAM*, led by the Norwegian ship operator Kolumbus. Since 2022, the ferry, *Medstraum*, carries 140 passengers at a service speed of 23 knots[84]. Another Norwegian fast-ferry operator, Norled, has launched an innovative battery replacement system. A robotic charging station swaps out the batteries while at quay, thus, extends the operating range of electric high-speed vessels[85].

In the *SeaZero* project[86], a Norwegian consortium develops a zero-emission design, based on batteries, for the coastal route vessel Hurtigruten, carrying around 500 passengers and 150 Euro-pallets. Key enablers are innovative onboard energy reducing measures and port infrastructure solutions.

Given that charging infrastructure is available, Stena Line plans to launch the battery powered ship *Electra* on their route Gothenburg-Frederikshavn by 2030[87]. In a research project, financed by the *Swedish Energy Agency* and led by ABB, electrification of the Gotland ferries was evaluated[88]. The study highlights that operational data is crucial to create insights on how to support part-electrification of larger ferries. Key input data includes port energy consumption, grid limitations, load/charge demand profile for ferries, PV solar plants, as well as energy storage on board and in port.

Denmark's first all-electric ferry started to operate in 2019. By the end of 2022, there still exists only a few electric ferries that allow the transport of cars. However, with 25% governmental financial support, new electric routes are being developed, including four conversion projects and ten new-builds[89].

In Finland, FinFerries operates two battery-hybrid vehicle ferries. Elektra, built in 2017, was the first ferry of this type built in the EU, and the second in the world. The Altera ferry, built in 2022, has a battery capacity of 1.2 MWh, which can be charged with shore power in only a few minutes. The ferries are also equipped with diesel generators, operating as backup and when sailing in severe conditions[90].

In Iceland, electrification started in 2015 with a fully electrified whale watching ship, as a result of the Nordic Innovation project *RENSEA*[91]. A regenerative plugin hybrid-electric drive enables battery charging from shore and from excess wind during sailing. Iceland's first (and only) all-electric ferry was launched in 2019, with a battery capacity of 3 MWh. Owned by the Icelandic Road and Coastal Administration, it operates between the mainland and Vestmanna Islands. To begin with, the operation relied on both batteries and diesel fuel, but after having built electrical towers in the two harbours, the reliance on electricity vastly increased[92]. Further electrification of state-owned vessels is planned for but not yet initiated.

6 Alternative fuels and end-use technologies

According to DNV's *Alternative Fuel Insight,* by June 2023[93] the global uptake of alternative energy carriers in the shipping sector is mainly limited to batteries, LNG and methanol. Batteries are installed on almost 800 ships and with 250 on order. More than 60% of the ships with installed batteries are operating in Europe, and of these more than 50% in Norway. For methanol there are 170 ships on order, however less than 25% are planned for operation in Europe. For LNG there are more than 500 ships on order, and over 400 in operation, of which 20% are operated in Europe. The operational area of LNG-fuelled ships has changed significantly since 2000, when the first ship (excluding LNG tankers) was launched in Norway. In 2016, 80 ships were fuelled by LNG, of which 70% operated in Norway, while today this share is 7%. This illustrates the important role of first movers for a global uptake of novel alternative fuels and energy solutions[94].

In this chapter, examples are given of pioneering uptakes of alternative fuels in the Nordic fleet, including H_2, NH_3, methanol and biofuels, as well as development of end-use technology.

6.1 Ships

6.1.1 Hydrogen

Hydra[95] – the world's first H_2-powered ferry – has entered into regular traffic in Norway, operating on a mix of H_2 fuel cells and batteries. The ferry is a result of the development contract with the Norwegian Road Administration, constituting a requirement of at least 50% operation on liquid H_2 (LH_2) on national roads. In addition to major technology advancements, significant effort has gone into developing rules and regulations. Since there is no production of LH_2 in Norway today, the fuel is supplied from Germany.

In 2022, Enova approved support for three H_2-powered ships (and five H_2-hubs with aims to produce H_2 for maritime transport). With additional support from Innovation Norway, Samskip aims to build the world's first container feeder operating on H_2. The vessel, sailing between Oslo and Rotterdam, will operate on H_2 fuel cells and batteries. Samskip has an intention agreement with the H_2 hub Agder on H_2 supply[96].

Another Norwegian consortium aims to develop a complete H_2 value chain for a zero-emission cruise ship featuring fuel cells and electric propulsion, as well as making H_2 available to the wider maritime market[97].

In 2021, a Norwegian shipowner received Enova funding to build the world's first ocean-going fishing vessel operating on H_2, but in early 2023 the project was cancelled[98]. One stated reason is the uncertainty in H_2 logistics. However, the main explanation was the much higher costs than initially predicted, partly due to yards adding costs to handle uncertainties. For the same reason, yet another ENOVA supported project might also be cancelled, which was aiming for the world's first H_2-operated bulk ship[99].

In Sweden, Gotlandsbolaget has launched its *Hydrocat*[100] – the world's first H_2-powered, large-scale, high-speed catamaran. It will be equipped with a multi-fuel gas turbine that can operate on H_2 or other green fuels, and will be able to sail at 35 knots, carrying 1,650 passengers and 450 passenger cars.

The EU project *HyEkoTank*[101], aims to demonstrate a 2.4 MW H_2 fuel cell system on a Swedish tanker ship. Fuel cells and compressed H_2 tanks are delivered by a Norwegian and a Finnish company, respectively. Another EU project, *Ship-aH₂oy*[102], is a pioneering initiative to introduce liquid organic H_2 carriers (LOHC) for maritime use. The system, where H_2 is stored in an organic oil, released onboard, and fed to a solid oxide fuel cell, will be demonstrated on a Norwegian service vessel for the offshore wind sector.

6.1.2 Ammonia

As for H_2, there is a lack of regulations for the use of NH_3 as ship fuel. Recently, DNV and the Nordic countries prepared an IMO submission on draft Interim Guidelines for NH_3 as a maritime fuel. In the process of implementing NH_3, Norway benefits from experiences with LNG as ship fuel, as well as the use of NH_3 as refrigerant on fishing vessels, and Yara's production and ship transport of NH_3 for use in land-based industry.

Norwegian Höegh Autoliners aims for NH_3-ready car carriers in 2026, equipped with multi-fuel engines[103]. Together with North Ammonia they have announced a partnership for the supply, distribution, delivery, and use of green NH_3. This will enable Höegh Autoliners to meet their goal of powering at least 5% of their deep-sea operation with green NH_3 by 2030, as part of their *First Movers Coalition Pledge*. Grieg[104] has ordered two large bulk ships, with engines prepared for conversion to NH_3. Skarv Shipping's[105] next short-sea bulk carrier will be equipped with NH_3 engines, 5 MWh batteries, and possibly also rotor sails.

Within the Norwegian *Green Shipping Programme* (GSP), an interdisciplinary group of 22 actors studied possibilities and barriers, including pilot studies, to convert parts of the deep-sea fleet to NH_3 operation[106]. The general conclusion is that it is technically and operationally doable, but there is a need for increased CO_2 taxes, and access to NH_3 in ports around the globe. Another GSP pilot study aims for NH_3-powered offshore service vessels, e.g. vessels for installing and operating wind parks[107].

The Norwegian Viridis Bulk Carrier and Amon Maritime have received DNV's Approval in Principle (AIP) for their design of what can be the world's first NH_3-powered short sea bulk ship[108]. DNV has also granted an AIP for an NH_3-powered gas carrier design developed through the Nordic Innovation project *NoGAPS*[109].

The Finnish shipping company Meriaura[110] will order an NH_3-powered cargo ship, equipped with multifuel engines. Green North Hydrogen Energy will supply green NH_3. The *GreenBalticCruising* project[111] addresses techno-economic and safety solutions for an NH_3-powered cruise ship route across the Baltic Sea.

Through support from the Icelandic Energy Fund, the seafood company Samherji aims to retrofit a trawler with a new dual-fuel Wärtsilä engine, with a short-term goal of operating on locally produced NH_3[112].

6.1.3 Methanol

For the use of methanol as a ship fuel, Sweden has been a pioneer. The RoPax ship Stena Germanica[113] has partly been running on methanol since 2015. In 2021, a pilot boat owned by the Swedish Maritime Administration, was converted to methanol operation. Apart from these two ships, methanol is still primarily used as fuel on methanol tankers, the first one being the Norwegian Westfal Larsen[114] in 2016. However, DNV reports[115] on almost 200 ships with methanol-ready engines being contracted until 2028[116], most of them containerships, but a scattering of orders in other sectors such as bulk and offshore.

The Danish-based Mærsk have ordered 19 container vessels with dual-fuel methanol engines, with the first ship to be launched in 2023. For the ship's first trip, from South Korea to Denmark, bio-methanol produced from biogas, being captured from decomposing organic landfill waste, will be used. The Norwegian-based MPC Container Ships and the North Sea Container Line aim to launch the first North Sea green corridor, including Norway's first methanol-powered container feeder ship[117]. Kongsberg Maritime, Norway, will supply design and equipment for three methanol-ready tanker ships, being built for the Danish tanker operator Tärntank, and will be used on time chartering by the Finnish refinery Neste[118].

Inspired by Stena Germanica, and financed by Energy Cluster Denmark, the possibility to retrofit a Læsø ferry to run on methanol-powered fuel cells was evaluated[119]. As a proof of concept, it may serve as inspiration to over 50 other ferry routes in Denmark alone, and over 1000 throughout Europe. ColorLine[120] has reviewed various zero-emission fuels for retrofitting their high-speed ferry, sailing at 27 knots between Kristiansand and Hirtshals. Methanol (and/or batteries) came out as most promising, however, not yet economically feasible. The world's first methanol-ready cruise ship is assembled at a Finnish yard[121]. The luxury residence vessel Njord[122], originally planned for LNG, is now designed for e-methanol/bio-methanol operation, giving it access to Norway's world heritage fjords.

The Danish shipping company Esvagt and the offshore wind company Ørsted have joined forces to realise the world's first SOV operating on green e-methanol, to be produced from wind energy and biogenic carbon[123]. The Norway-based offshore service firm Cecon[124] has entered into an agreement for the construction of a methanol- and battery-powered cable installation vessel.

Sweden participates in the EU project *HyMethShip*[125], focusing on using methanol as a *H_2 carrier* and re-using the CO_2 for green methanol production. Methanol is reformed on board into H_2 and CO_2, where the H_2 is used for propulsion and the CO_2 is temporarily stored on board.

The Icelandic company UR Seafood received founding from the *National Energy Fund* to retrofit a freezer trawler to operate on green methanol. Due to limited methanol supply, the initiative has been delayed. However, key stakeholders, led by the National Power Company, are developing a case for methanol production in the northeast of Iceland, specifically aimed at maritime off-takers[49].

6.1.4 Biofuels

A recent white paper from DNV[126] concludes that biofuels will likely play an important role in shipping over the coming decades, due to their ability to be used as "drop-in" fuels. However, there are limits related to production capacity of sustainable (advanced) biofuels, competition from other sectors, and a need for case-by-case evaluation to ensure compatibility with the application/equipment on board.

The follow-up of the *Swedish maritime roadmap*[127] shows an increased use of biofuels. The tanker vessels owned by Furetank, Tärntank and Thun, as well as Destination Gotland's passenger ferry, have started to blend in LBG in their LNG-powered ships and have plans to gradually increase the amount. The Norwegian Havila Kystruten also plans to successively mix LNG with LBG[128].

The Swedish-owned Furetank[129] is piloting a waste-based fuel produced by Equinor's refinery in Mongstad, Norway. The fuel consists of 30% cooking oil and 70% gas oil and is used in existing dual-fuel engines normally operating on LNG/LBG or gas oil. Since 2022, the Norwegian Höegh Autoliners[130] offers their customers carbon-neutral cargo transport, by operating solely on sustainable biofuel, derived from waste oil in food manufacturing and industrial applications.

The Finnish refinery Neste has switched two of its tanker vessels to operation on biofuel, produced at Neste's refinery[131]. The fuel, co-processed from bio-crude oil, enables 80% GHG emission reductions. The Finnish shipping company Langh Ship[132] has started to operate their short sea container vessel on biofuel. For Finland to become carbon neutral in 2035, the use of liquid biofuels and biogas is expected to increase, especially in heavy road, maritime and air transport[68]. In 2023, Wasaline's RoPax vessel Aurora Botnia[133] started using biogas one day a week, supporting the green corridor initiative on the Vaasa-Umeå route.

The Norwegian government has proposed to include domestic shipping in the turn-over requirements on advanced biofuels in the transport sector[134]. The Norwegian Maritime Authority has submitted a regulatory proposal[135] for the *Zero-emission requirements in Norwegian Heritage Fjords by 2026*, including a transitional arrangement that permits the use of biogas for ships of over 10,000 GT until 2035. In the government's proposal on zero-emission requirements for ferry tenders from 2024, it is suggested that biogas is to be equated with H_2 and batteries as zero-emission technology[136].

6.1.5 Other options – nuclear and wind

Wind-assisted propulsion is seeing growing support from innovators and first movers across the industry, and Nordic countries are all well represented[137]. Even though associated with many barriers, nuclear power is also gaining interest as a pathway to zero-emission ships, by mitigating competition for sustainable biomass and renewable electricity.

The Finnish wind power company Norsepower[138] has installed their rotor sails on two Scandlines ferries, and has secured fundings to scale up production, expand business area, and strengthen their R&D. The Norwegian shipping company Odfjell will install a suction sail system on a chemical tanker, making it the world's first of its kind. *WHISPER*[139], an EU project coordinated by Iceland, aims to demonstrate a tiltable wing-sail and a containerised wind turbine on a bulk and container ship. Also supported by EU, Wallenius Wilhelmsen leads a project on building the world's first wind-powered RoRo vessel *Orcelle Wind*[140].

The potential for nuclear propulsion is being evaluated by major classification societies, including DNV[141], LR[142], ABS[143], and RINA[144]. In the project *NuProShip*[145] (Nuclear Propulsion of Merchant Ships), Norway and Sweden collaborate on studying the feasibility of three different nuclear reactor concepts within the Generation IV domain. As a spinoff, NTNU has together with a fishing vessel company joined forces to build a 150-tonnes mini reactor at about 10 MW for larger trawlers.

6.2 End-use technology

Several end-use technologies are being developed within the Nordics, primarily related to NH_3 and H_2. Some examples are given below.

6.2.1 NH_3 and H_2

In Norway, DNV has recently granted an AIP for Hav Hydrogen's containerised H_2 fuel system[146] (with up to 1 MW fuel cell), and for Alma Clean Power's NH_3-fuelled solid oxide fuel cell[147]. Furthermore, Amogy has received an AIP from LR on their NH_3 power pack[148], in which liquid NH_3 is cracked to H_2 on board, before entering a proton exchange membrane (PEM) fuel cell. Full-scale tests are performed at *Stord*, and the first demonstration will be on an existing tugboat. The first pre-order is signed with a Norwegian shipowner.

Through the EU project *H_2NOR* [149], Corvus Energy launched the first H_2 fuel cell that can be installed below deck without special machine room requirements, enabling efficient integration inside the ship's hull. It was achieved by optimizing the safety of Toyota's mature car fuel cells to fit a maritime environment.

Development and full-scale testing of NH_3-powered engines is being performed by Wärtsilä[150] (four-stroke) in Norway and Finland, and by MAN-Energy[151] (two-stroke) in Denmark. These dual/multi-fuel engines are expected on the market during 2024-2025. *Through the Norwegian research project AMAZE*[152], Bergen Engines *is working on innovative NH_3 combustion concepts to be applied in an engine that can seamlessly switch between NH_3, diesel and biofuels.*

An NH_3 cracking system is developed by the Norwegian Pherousa Green Technologies[153], for use of NH_3 as a H_2 carrier in deep sea shipping. The cracking enables engines to operate on an NH_3-H_2 fuel mix, minimising the amount of pilot fuel. It also enables the use of pure H_2 in PEM fuel cells.

6.2.2 <u>Methanol</u>

In 2022, Wärtsilä delivered *their first methanol powered engine*[154], and a dedicated fuel supply system. The Danish Blue World Technologies develops a methanol PEM fuel cell [155] for use as an auxiliary power unit on ocean-going vessels. By combining several 200-kW modules, the unit can deliver power in the MW range.

7 Alternative fuels – production, distribution and supply

A report by MENON[156], performed within the *Nordic Roadmap* project, gives an overview of 140 existing and planned projects for alternative fuel production in the Nordics towards 2030. The report includes projects on H_2, NH_3, methanol, and to some extent also biofuel. For each of the Nordic countries, this chapter summarises major findings from the report, and provides some recent updates (per June 2023) related to the projects included in the report, as well as some new projects.

7.1 Existing and planned production projects

Figure 7 shows the 140 projects, divided on countries and type of fuel. The main conclusions are:

- H_2 projects dominate in all countries, with Norway having the largest number of projects.
- the total planned H_2 production capacity in 2030 is 150 TWh, being largest in Denmark.
- for most projects, no information is given on how much of the produced H_2 is for maritime use.
- despite the focus on H_2 production, it does not mean that NH_3/methanol will not be available in the ports since these fuels can much more easily be transported to the ports from elsewhere.

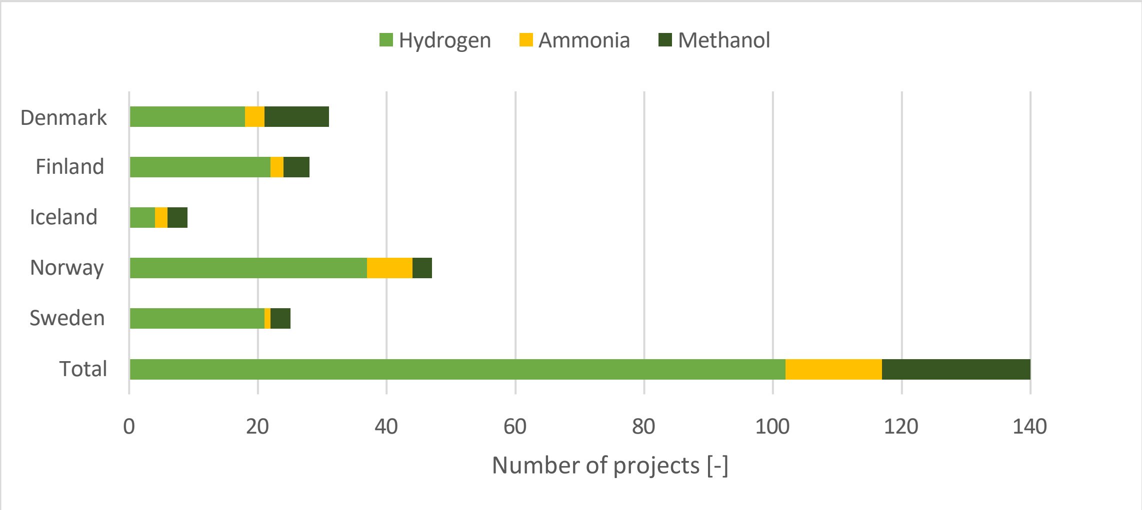

Figure 7: Number of fuel production projects in each country, based on data from MENON[156]

7.1.1 Norway

- H_2 is considered an important part of a diverse energy mix. Of the 47 projects, 37 are related to green/blue H_2 production, while there are 7 projects on NH_3 and 3 projects on methanol.
- Differently from other Nordic countries and reflecting Norway's position as a major oil and gas producer, a large blue production capacity is planned. Even though only 5 projects are "blue", the volume constitutes 60%, mainly from two H_2 projects and one NH_3.
- Infrastructure development is needed since production is not necessarily located near end-users.
- Almost all electricity production comes from renewable sources (almost 90% from hydropower).
- The use of pioneering technologies, including solar, floating wind and energy storage, is based on experience and innovations made in the oil and gas sector.

Some updates on H_2 production:

- The Norwegian H_2 project at Hellesylt[157] will be realised, as an important pilot project to demonstrate local production and use of green H_2.
- Norwegian H_2[158] has announced plans for one of the largest production facilities for green H_2 in the Nordic region, with an annual production of 40,000 tonnes in Ørsted. A capacity of 20 MW has been granted, and an application for a further 250 MW capacity is being processed.

- Aker Horizon[159] has received financial support from Nordic Innovation for their planned H_2 plant in Rjukan, producing 9 tonnes/day. A final investment decision will be taken in 2023.
- Stord Hydrogen[160] has opened their production plant for green H_2, which will primarily be used for H_2 operation in fuel cells and engines at the full-scale test centre at Stord (Energy House). It will also be transported as containerized compressed H_2 to other customers
- Rørvik H_2 Hub[161] has taken yet a step forward by signing an intention agreement on using the electrolysers from Hystar – a company originating from researchers at SINTEF.
- Yara's ENOVA-supported initiative, to build and produce green H_2 at Herøya[162] was planned to be operational in 2023. The 24 MW electrolysis pilot would be the world's largest.

Some updates on NH_3 (and H_2) production:

- Aker Horizon has entered a 10-year power purchase agreement with Statkraft, securing a significant amount of renewable energy to their planned 600-MW green H_2 and NH_3 plant[163].
- Fortescue Future Industries has also secured renewable power for its planned 300-MW green H_2 and NH_3 facility in Holmaneset[164], through a long-term agreement with Statkraft.
- Höegh Autoliners and North NH_3 have entered a partnership for the supply, distribution, delivery, and use of green NH_3, to be produced at North NH_3's planned facility in Arendal[165].
- Neptun Tromsø AS was established in 2022 for building up a production plant for green NH_3 in Tromsø[166], based on local renewable electricity, and to be used as maritime fuel.
- In Skipavika[167], a plant producing 100,000 tonnes green NH_3 is planned for 2026. The NH_3 will function as a battery for excess offshore wind when there is a "low" demand in the power grid.
- The Barents Blu[168] aimed to become Europe's largest plant for blue NH_3, including storage of CO_2 in Barents Sea. However, since their grid application was rejected, the project must be scaled down.

Some updates on methanol production:

- Glocal Green and Norwegian Hydrogen collaborate on large-scale production of bio-e-methanol. Glocal Green will produce bio-methanol based on biological waste and residual industrial raw materials, while Norwegian H_2 will produce green H_2 to be mixed into the final product. The first factory on Øyer[169] aims for 170,000 tonnes/year, with the shipping sector as main end-user.
- Glocal Green[170] has been tasked by Stranda municipality to evaluate the potential for bio-methanol as a solution for the zero-emission requirement in Heritage Fjords.

7.1.2 Denmark

- Of the planned projects, 18 are related to H_2, 10 to methanol and 3 to NH_3.
- Renewable energy production focuses on decentralised wind farms, and solar farms are emerging.
- 30% of the gas grid is biogas, supplied by 52 national biogas plants.
- CO_2 could be captured from the biogas and used in PtX fuel projects (i.e. CCU).
- Political decisions, including financial supports, will promote PtX and the production of green fuels.
- Strong energy infrastructure connecting it to many European markets.
- Salt caverns available for green H_2 storage.
- Greenland considers an 800-MW hydropower plant to produce H_2, and possibly NH_3 or methanol.

Some updates on PtX fuel production:

In April 2023, the Danish Energy Agency opened the Power-to-X tender[171], which offers support for companies' production of green H_2. There are several plans for large-scale e-fuel production sites.

- HØST PtX Esbjerg[172], with Mærsk and DFDS as partners, plans for a 1-GW plant, producing 600,000 tonnes of NH_3 for agriculture and shipping. Agreement on logistics and offtake in the maritime sector has been signed, as well as a connection agreement with a TSO Operator[173].

- The world's first "dynamic PtX plant" is being built in West Jutland[174]. It will run on electricity generated by 12 MW of existing wind turbines and 50 MW of new solar arrays, with an annual production capacity of about 5,000 tonnes of green NH_3. With dynamic plants, the production can be geared down when there is lack of local renewable energy available (wind, sun), making them different from the "normal" PtX plants that are directly connected to the grid.
- European Energy, a Danish company, and Port of Aalborg have signed a Letter of Intent (LoI) for a 120-MW electrolysis plant and an associated e-methanol plant producing 75,000 tonnes yearly[175].
- Mærsk Growth has invested in a Danish company developing a method to produce carbon-neutral biofuels from non-edible biowaste[176].

7.1.3 Finland

- Wind power production is increasing, and wood fuel resources are important.
- The H_2 strategy on production, use and export of clean H_2 is based on large wind energy availability, a strong electricity grid, and a well-working H_2 value chain.
- 22 projects are related to H_2 production, of which a few also aims for NH_3 production.
- 4 methanol projects: 2 on green e-methanol and 2 on bio-methanol.
- A full-scale demonstration project for advanced biofuels (biogas, biodiesel, bio-oils, bioethanol).

Some updates on H_2/NH_3 production:

Finland's H_2 strategy[177] includes goals to greatly expand the production of low-carbon H_2 and e-fuels to support emissions reductions in hard-to-abate sectors like shipping.

- Flexens has launched an expansion of their Kokkola project[178], producing H_2 alongside NH_3.
- Hy2gen plans an 800-MW (60,000 tonnes) green NH_3 facility near Kokkola port. The H_2 feedstock will be produced by Plug Power, who also plans for H_2 production in Kristinestad and Porvoo[179].
- ET Fuels (Ireland) plans to produce synthetic methanol for use as ship fuel in Ranua[180]. The plant will be powered by up to 50 own wind turbines, and use CO_2 recovered from industrial processes.
- P2X Solutions is commissioning an industry-scale green H_2 plant in Harjavalta, planned for 2024[181].

The *Finnish Hydrogen Cluster*[182] highlights the need for collaboration with neighbouring Nordic countries to build regional "H_2 hubs", which is especially important for Finland located on the periphery of Europe.

- Finland leads BalticSeaH_2[183], a collaborative effort with 40 partners from 9 countries, aiming to create a large-scale cross-border H_2 valley. One key objective is emission reduction from shipping.
- Gasgrid Finland[184] is preparing H_2 infrastructure, including the Nordic-Baltic Hydrogen Corridor, Baltic Sea Hydrogen Collector, and Nordic Hydrogen Route.

7.1.4 Iceland

- Almost 100% renewable power production, based on hydropower and geothermal energy.
- Policy of increased diversity and flexibility in the energy system, e.g. larger uptake of H_2.
- The H_2 vision for 2030 aims to contribute to reduced emissions from transport.
- Of the 9 projects on alternative fuel production, four are on H_2 and two on NH_3.
- Of the three methanol projects, one is based on blue production (i.e. using natural gas and CCS).

Some updates on fuel production:

- ATOME Energy[185] has secured renewable energy and first offtake for Iceland's large-scale green NH_3 plant. This includes up to 40 MW of geothermal and hydroelectric power from 2026, and some of the NH_3 will be used to power fishing vessels owned by Samherji.
- Several of the Icelandic projects are initiated by Landsvirkjun, the national power company, but in close cooperation with end-users to understand future needs. For example, together with the container transport company Eimskip they are working on a *methanol* project[186].

7.1.5 Sweden

- Of the 25 projects, most of them (21) are for H_2 production, one for NH_3 and three for methanol.
- Many of the H_2 projects are focused on industrial applications, such as green steel production.
- The planned H_2 hub in Luleå is primarily for maritime applications.
- Much of the H_2 production is near ports or bunkering sites, implying a potential for maritime use.
- The methanol production (small) is intended for use as maritime fuel.
- There are some projects related to production of bio-methanol from forest residues.
- Need for development of H_2 storage, due to lack of geological storage formations (salt caverns).

Some updates on methanol production:

- Liquid Wind[187] has partnered up with Umeå Energi to build Sweden's third e-methanol plant, for use as ship fuel, following Örnsköldsvik and Sundsvall projects already being developed.
- The Ørsted-controlled facility in Örnsköldsvik, supported by "Klimatklivet" through the project *FlagshipONE*[188], aims to become Europe's largest e-methanol plant for the shipping sector (50,000 tonnes yearly from 2025). The plant will use CO_2 from Övik Energi's district heating production.
- Sundsvall Energi and Umeå Energi will deliver biogenic CO_2 to the two other plants. This is in line with the Swedish government's wish for expanded investments in bio-CCS for e-fuel production.

Some updates on H_2 production:

- A 20-MW electrolyser will be operational at the Hofors mill already in 2023[189].
- The H_2 Green Steel plant in Boden aims for an 800-MW electrolyser[190]. A step towards realisation is a partnership with Finnish Fortum, ensuring short and long-term carbon-free electricity.
- *SoutH$_2$Port*[191] aims for a 600-MW H_2 electrolyser in Søderhamn, connected to offshore wind in the Baltic Sea. An estimated daily production of 240 tonnes makes it one of Europe's largest. However, realization is linked to development of further processing and/or use of green H_2 in the same area.
- Vattenfall has initiated a project to produce H_2 in connection with a nuclear power plant[192].

7.2 Fuel infrastructure

Most Nordic ports have bunkering facilities for conventional fuel oils, either as shore-to-ship, truck-to-ship or ship-to-ship. LNG bunkering is available in about 30 ports (of which 18 in Norway), mostly as tank-to-ship, and a few ship-to-ship. A future need for more frequent, or higher-capacity, facilities for bunkering and shore power is expected, driven by the low-energy density of future fuels and power generation.

There are several Nordic initiatives to establish bunkering infrastructure for zero-carbon fuels. A few facilities are in operation either as a terminal or a bunker ship. Within the Nordic Roadmap project, interviews were performed with 24 ports[156], on their short-term plans for supplying H_2, methanol and NH_3.

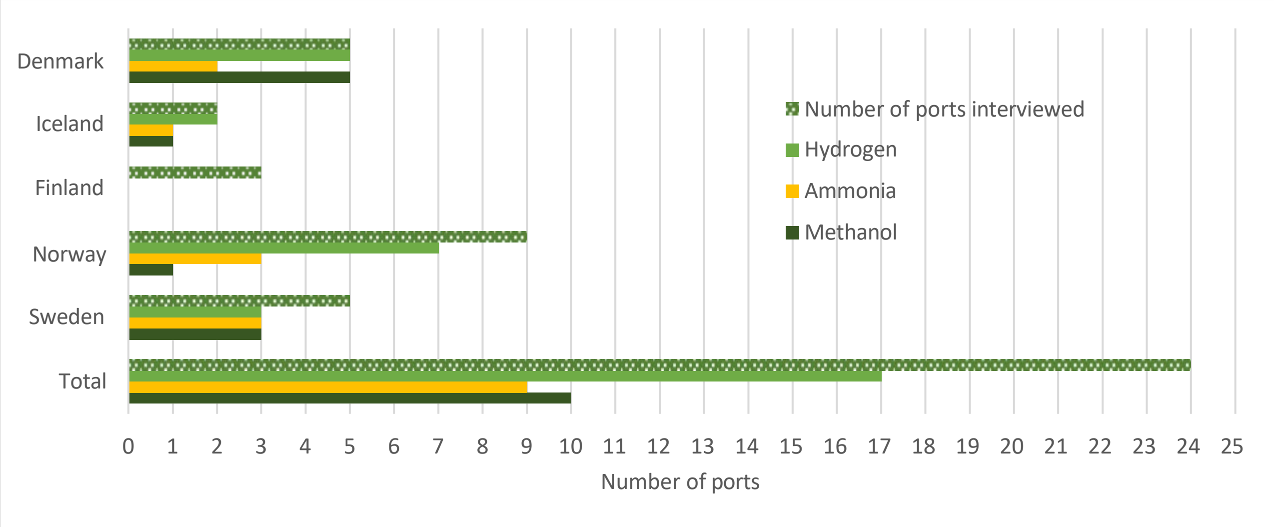

Figure 8: Results from interviews with Nordic ports on plans to supply alternative fuels, based on data in MENON[156]

The main findings were as follows (see also Figure 8 and Figure 9):

- 17 ports plan to supply at least one of these fuels by 2030, with plans for H_2 supply in all of them.
- In Sweden, the 3 ports with plans for alternative fuel supply intend to supply all three fuels.
- In Norway only one of the seven ports has plans for methanol supply.
- Of the 17 ports with plans to supply H_2 as a bunker fuel, 12 ports also aim for H_2 production.

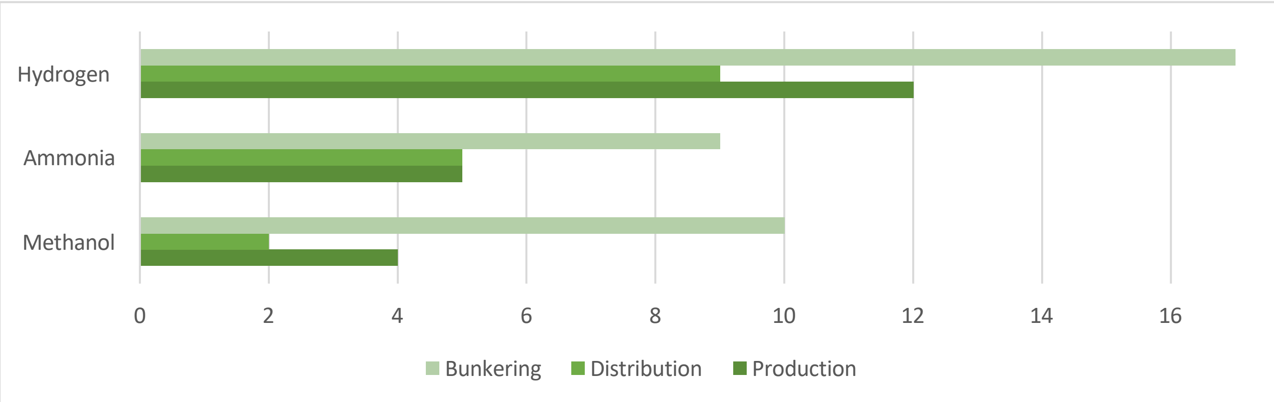

Figure 9: Results from interviews with Nordics ports, on their plans for not only offering bunkering of alternative fuels but also production and/or distribution of them, based on data in MENON[156]

The need to develop alternative fuel infrastructure is highlighted in the Nordic countries' national climate strategies and transport plans. To realize this, there is a need for close cooperation among shipowners, operators, ports, fuel producers/distributers, technology suppliers, legislators, and researchers. While such collaboration projects between Nordic countries are limited, there are several on a national level. The Norwegian Government's *Green Platform Initiative* supports such projects, as exemplified further below.

7.3 Offshore energy supply

Below some examples are given on innovative concepts for supplying ships' energy needs offshore.

7.3.1 Floating ports

The Swedish company Sea Technology[193] sees floating ports or terminals as a solution for handling the increasingly larger container vessels, being too large for many ports. Their solution is to use electric "feeder vessels", sending containers from the floating terminal to different ports in Denmark, Norway and Sweden. Floating energy supply could also be an alternative for the increasingly larger cruise ships. Also, together with several partners, Sea Technology and RISE are working on concepts to produce, store and distribute energy offshore, for example as a node for offshore wind farms.

7.3.2 Floating charging

As the offshore wind industry is blooming, so is the demand for green operation of support vessels. One solution is to make electric charging available offshore. In the Norwegian Green Platform project *Ocean Charger*[194], VARD, together with a large industry and research consortium, will develop, test, validate and commercialize a charging solution for offshore wind supply ships. The potential for expanding its use into other short sea shipping segments will also be evaluated.

Stillstrom[195], a Danish innovative spin-out from A.P. Moller Maersk, has developed an offshore charging buoy. It is designed to eliminate emissions from offshore idling vessels and facilitate offshore charging. A first concept is tested at an offshore wind park. Other possible applications include electrifying outside ports, energy islands, and near-shore locations, thereby also addressing congestion and limited space.

The Norway-based Ulstein[196] has developed a concept design for a 149-m replenishment, research and rescue ship powered by a thorium Molten Salt Reactor (MSR) that can be used to recharge battery-driven cruise ships at sea. The Danish company Seaborg[197], has signed an LoI with Norsk Kjernekraft with the aim of building nuclear power plants on barges in Norwegian fjords.

7.3.3 Floating H_2/NH_3 production

DNV has given an AIP for a floating NH_3 production plant based on offshore wind[198]. The FPSO (Floating Production Storage and Offloading) plant is developed by SwitchH_2 (Netherlands) and BW Offshore in Norway. The produced NH_3 is intermediately stored until transported on tankers. Another similar concept, the *P2X Floater*[199], is developed by the Norwegian H_2Carrier and Anori, Greenland. The NH_3 is produced on a berthed ship, using onshore wind power, and can be used as a "battery" for excess/variable power from the wind plant, supplying both ships and industries.

In the Green Platform project *Ammonia as Hydrogen vector*[200], a Norwegian consortium develops technology to enable onboard conversion of green NH_3 into H_2. The installation will be on a FSRU (Floating Storage and Regasification Unit), which today is used for receiving LNG. The NH_3 will be transported by ship to the FSRU where it is stored and converted into H_2 and sent ashore in H_2 pipelines.

According to a DNV study[201], the North and Baltic Seas would benefit greatly from a *Specification of a European Offshore H_2 Backbone*. H_2 production at offshore wind farms is an appealing option especially at distances more than 100 kilometers from shore, given the lower costs of H_2 transmission compared to electricity, and the potential for pipelines to aggregate H_2 production from several offshore windfarms.

7.3.4 Energy islands

Green energy from offshore wind farms has been a success story in Denmark, and the plans for establishing energy islands has gained focus on both national and European level. The plans include an artificial island in the North Sea, and the island of Bornholm in the Baltic Sea. The islands are set to become one-of-a-kind wind energy hubs, where the produced energy is gathered on the island, and then delivered to power consumers, or used to produce green fuels via a PtX facility. A total production of 6 GW was scheduled for 2030, with an increasing capacity towards 2040[202]. Recently, the government postponed the tender for the artificial island since the current concept was found to be too expensive and risky.

As frontrunners in offshore wind, the four countries of the *Esbjerg Declaration* (Denmark, Netherlands, Germany and Belgium) aim to jointly connect 65 GW of offshore wind energy by 2030 and 150 GW by 2050 by establishing interconnected energy hubs in the North Sea. In addition, 20 GW of H_2 production capacity on- and offshore should be developed by 2030[203].

7.4 Ports as energy hubs

As stated by IRENA[204], the decarbonisation of international shipping needs to be fuelled by investment in an efficient, safe, reliable and affordable supply of renewable fuels via sector coupling mechanisms among, for example, bunkering service companies, port authorities, utilities and the renewable energy sector.

The potential for sector coupling in ports is highlighted in most Nordic countries. According to the Swedish maritime competence centre *Lighthouse*[205], sustainable ports are considered central nodes for sector coupling and energy system integration as they host and serve multiple industries, including oil and gas facilities, maritime supply chains, road haulage, rail transports, cruise tourism, manufacturing sites, heat and power stations, and electricity grid and offshore wind operators. The Finnish Hydrogen Cluster[206] states that ports offer an excellent sector-coupling opportunity, by offering electricity, H_2 and/or synthetic fuels for ships, and linking the necessary shore-side facilities to municipal energy networks.

To establish shore power supply for cruise ships with large power demands, as well as charging facilities for battery-driven ships, a strong electricity grid in and around the ports is required to satisfy large peak power demands. To meet this challenge, sector coupling will be important, as well as utilising the interconnection of, and cooperation within, the Nordic energy system[62].

Sector coupling, e.g. through energy system integration, is the topic of several research studies, among them the Swedish project *Ports as energy nodes*[207], and the two Norwegian projects *Interport*[208] (Integrated Energy Systems in Ports), and *ACES*[209] (Accelerating Energy and Sustainability Transitions in Ports). A Danish research study[210], using Esbjerg as a case port, suggests climate partnership to advance sector coupling and integration in the port for the production on green fuels.

Esbjerg is an excellent example of a port's energy transition. From being Europe's biggest fishing port to becoming Denmark's oil and gas hub, and now being a world leading offshore wind port and a future PtX hub[211]. The port's ambition is to become a "green energy producing integrated self-sustained CO_2-neutral port". To limit investment risks, a flexible multi-purpose energy infrastructure will be built, e.g. a green electricity micro-grid and a green fuel/energy grid. The Danish port Hirtshals aims to become Europe's greenest port, through the *Greenport North*[212] project. Sector coupling is highlighted as key to optimise green supply to users and owners, including heat, electricity, gas, cold, H_2, oxygen, and biogas. Collaboration with ports around Kattegat, Skagerrak, and the North Sea will be established.

7.5 Bunkering hubs

The *Nordic Roadmap* project aims to develop a Nordic strategy for infrastructure development and for using ports as green corridors (see section 7.7) or green energy hubs. Differing from the energy hub concept (section 7.4), these hubs are focused on providing energy only to the shipping sector and are therefore here referred to as bunkering hubs. The top 20 potential Nordic bunkering hubs were identified, based on Nordic ship traffic in 2019[156]. A potential bunkering hub is defined as a port with significant energy demand from ships sailing from the port. These hubs might serve corridor routes, local ship operations, extensive international routes, as well as distributing fuels to surrounding ports.

Below, some examples of initiatives and projects on bunkering hubs are given, starting with Denmark.

Ålborg explores possibilities of storing green fuels in the port, to become a green hub[213]. Hanstholm aims to become Europe's first CO_2-neutral fishing port, with plans for a PtX plant to produce methanol and NH_3 and establishing a bunkering hub for fishing vessels[214]. Through the *Marco Polo* project[215] (Methanol Availability Readiness Cost Operationality for Port Logistics), Hanstholm and Frederikshavn are included in a study on how Danish ports can play a key role in reducing global CO_2 emissions, by local production of PtX fuels and for shipping captured CO_2 to storage offshore. In the *Bornholm Bunkering Hub* project[216], an international consortium performed a feasibility study on developing the Port of Rønne into a bunkering hub for green fuels, with a market of approximately 60,000 ships that yearly sail past the island.

Sweden's largest port, Gothenburg, aims to establish Europe's first bunkering hub for green e-fuels, and to become the primary bunkering hub for renewable methanol in Northern Europe[217]. Together with major industry players, an e-methanol value chain is set up. A milestone was achieved when the port hosted the world's first methanol ship-to-ship bunkering for a non-tanker vessel (previously bunkered from truck)[218].

In Norway, an industry consortium led by EXXON Norge has the ambition of producing H_2 and NH_3 at the Slagentangen terminal in the Oslo Fjord, and by that transforming it into a hub also offering low-emission shipping fuels. The final investment decision is to be made in 2024[219].

The Norwegian joint venture AZANE Fuel Solution leads the *AFBN* project on realising the world's first NH_3 Fuel Bunkering Network [220]. With financial support from the Green Platform Initiative, the first bunker barge will be developed, and tested in 2024. The NH_3 producer, Yara Clean NH_3, has pre-ordered 15 bunker barges, and has teamed up with NorSea Group for operation at their logistics bases[221]. AZANE and Equinor have established *AFNO 2030*[222], a project focusing on how NH_3 fuel can be used to decarbonise the Norwegian offshore sector, covering logistical optimization, operational planning, and safety aspects.

In *Zerokyst*[223], another Green Platform project, a broad Norwegian consortium works towards decarbonising the fishery and aquaculture sector. Besides developing H_2-electric fishing vessels, the focus is on production, storage and bunkering of H_2, and regional infrastructure for H_2 bunkering and battery charging.

7.6 Hydrogen valleys

A *H_2 valley*[224] is defined as a project that clusters several industrial and research initiatives to carry out pilot projects across the complete H_2 value chain, i.e. production, transport, distribution, (storage) and end-use. Five such projects are funded by Nordic Energy Research through H_2 Valleys as Energy Hubs – by 2030 and 2040[225]. Table 1 shows the main topic and the Nordic countries involved in each project.

Table 1: Overview of projects funded by Nordic Energy Research, within the program H_2 Valleys as Energy Hubs[225]

Project	Topic	Countries
Nordic H_2 hubs - Roadmaps towards 2030 and 2040	Five case studies to improve understanding on how to ensure successful cross-sectorial linkage between Nordic H_2 hubs across land and sea.	All
Rally to the Valley: Establishing H_2 Value Chains for the Nordics	Particular focus on the role of the maritime sector. Insights of optimal production of H_2, NH_3, and other e-fuels, including cost structures for production, storage, and transportation.	DK, FIN, NO
H_2, NH_3, and Methanol in H_2 Hubs in the Nordic Region	Three case studies of energy hubs, centred at ports in various Nordic locations, to learn how ports, surrounding areas and actors can scale up H_2 fuels and become fossil-free energy hubs.	SE, NO, IC
H_2 safety and improved permit processes	Strategy to delimit barriers for implementation of H_2 in the Nordic countries, from a permit, safety, and social acceptance perspective.	SE, FIN, NO
Material and structural integrity assessment for safe Nordic H_2 transportation	Safety issues (embrittlement) of H_2 pipelines, for use in regional and interregional large-scale transport and storage of pressurized H_2 gas.	NO, SE, FIN

The EU initiative on H_2 valleys aims to establish operative local H_2 value chains through collaboration among various sectors and industries[226]. The *Mid Norway H_2 Valley*[227], led by RENERGY, represents a value chain consisting of established and financed projects, covering production and use within land and sea transport, and industry. The plan is to produce, distribute, store and use 20,000 tonnes/year by 2030.

7.7 Green corridors

Green shipping corridors involve binding cooperation between different actors in the value chain, to work towards decarbonisation on a given route, e.g. through provision of infrastructure, contractual frameworks and regulatory measures. They are characterized by the participating actors who are jointly able to address barriers. Green corridors can give shipping companies, ports and cargo owners incentives to invest in low- and zero-emission ships for passenger and cargo transport[228].

7.7.1 Strategies and cooperation

The global progress report on *Green Shipping Corridors*[229] states that the regional approach is particularly strong around the Baltic and North Seas, with collaboration between Nordic countries. The Nordic region is considered well-suited for establishing green corridors, to initiate a faster transition towards green ships on all routes and for all ship types. The Nordic climate ministers have agreed on working together to establish green corridors between ports in the Nordics[230]. All Nordic countries signed the *Clydebank Declaration*[231] under COP26, implying a commitment to cooperate with one or more countries on green corridors, and by that contributing to the establishment of at least six corridors globally.

The Swedish Transport Authority is assigned as national coordinator for green shipping corridors[229]. Eleven high-potential corridors have been identified, based on technological and stakeholder readiness, and public mandate to enact change. According to the Danish Maritime Authority[232] a national action plan is being developed, aiming to establish green corridors from Danish ports, and to play a central role in the international development. *Maritim21*[233], the Norwegian strategy for R&D&I in the maritime sector, emphasizes the need for establishing green corridors through national and international collaboration.

During Finland's presidency of the Council of the Baltic Sea States[234], the expert group on *Sustainable Maritime Economy* continues to chart clean transport corridors, defined as green corridors in the Clydebank Declaration. The *Clean Arctic Alliance*[235], proposes a number of domestic and international actions to facilitate the establishment of green shipping corridors in Arctic waters.

7.7.2 Examples of initiatives

Examples of green shipping corridor initiatives, involving one or two Nordic ports:

Gothenburg Port has signed a Memorandum of Understanding (MoU) with Rotterdam Port to realize a green corridor, and also with the North Sea Port (Ghent)[236]. The ports are making adaptations to infrastructure, including bunkering regulations, and increasing port fees discounts for ships using cleaner fuels. Business Finland supports a project on a carbon-neutral route between Turku and Stockholm[237]. An MoU has been signed by Finnish and Swedish stakeholders, aiming for a Green Shipping Corridor between Umeå and Vaasa, by 2030[238]. The ports of Helsinki and Tallinn (Estonia) have led an agreement to create a green corridor[239].

The Norwegian-based MPC Container Ships, and North Sea Container Line (Netherlands), aim to launch a North Sea green corridor based on methanol[240]. The following three examples of Norwegian national corridors, have all started as pilot studies in the Norwegian Green Shipping Programme[241]. Even though initiated by the cargo owner, the GSP cooperation platform is a key element for realization.

- ASKO, a grocery supplier, drives a project between Horten and Moss in Norway, where two autonomous electric vessels will transport cargo across the Oslo fjord.
- Yara has initiated the Yara Birkeland, an autonomous-ready electric container ship transporting fertilizer from Porsgrunn to Brevik.
- Heidelberg Cement and the agricultural cooperative Felleskjøpet AGRI have established a joint effort requesting a zero-emission cargo ship.

Rønne, Bornholm, is one of the five ports in Northern Europe and Baltic Sea participating in the *European Green Corridor Network*[242], established by *Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping*. The aim is to demonstrate early commercialisations of alternative fuel supply chains, provide a roadmap for scaling the supply chains, and create a blueprint for rolling out corridors in other locations.

7.7.3 Feasibility

An assessment of potential green corridors was performed within the *Nordic Roadmap* project[156]. As a first step, 81 intra-Nordic ship traffic routes were identified as candidates based on AIS analysis of voyages in Nordic waters. Of these, 37 ports were chosen for analysis of barriers and for dialogue with stakeholders. Then, six green shipping corridors were selected, all having motivated stakeholders:

Stockholm - Turku, Sandefjord - Strömstad, Ystad - Rønne, Umeå - Vaasa, Hirtshals - Larvik, and an Arctic corridor. Barrier screenings were made at stakeholder workshops, identifying three key barriers:

- Financial gap between using conventional fuels and zero-emission fuels.
- Lack of fuel availability and bunkering infrastructure.
- Lack of safety requirements/regulations on board and on shore for NH_3 and H_2.

One recommendation to overcome the barriers is a "Nordic Playground", aiming at a unified approach on safety issues and GHG emissions accountability, and establishment of green fuel market and infrastructure.

To facilitate feasibility studies on green shipping corridors, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping has developed the *Feasibility Phase Blueprint*[243]. It aims to serve as a ready-to-use guide for any stakeholder, providing an approach to design and demonstrate the feasibility of green corridors. Another effort of this kind is ABS's *Green Shipping Corridors Simulation* service[244], designed to provide a simulation of various stakeholders involved and deliver data to support policy and investment decisions.

7.8 Port collaborations

Examples of port collaboration related to environmental actions and requirements:

- *Norwegian cruise destinations*[245]: In 2019, politicians and mayors from 15 cruise destinations agreed upon common environmental requirements. This includes, for example, obligations for cruise ships to use standardised OPS by 2025, and requirements for zero-emission solutions in all transport related to cruise ships (passenger buses, transport of goods, waste). Cruise ships that can document environmental measures will be prioritised in terms of, e.g., time of arrival and quay.
- *Oslo Fjord*[246]: Seven ports collaborate to reduce emissions in the Oslo fjord by 85% in 2030.
- *Environmental Port Index (EPI)*[247]: Developed by DNV and several Norwegian cruise ports, the EPI enables to characterise ships' environmental imprint during port stays, and to differentiate port fees. EPI is applied in 20 Norwegian ports and 3 Icelandic ports, with plans for further extension.
- *Clean Shipping Index (CSI)*[248]: The CSI, developed in Sweden, is an independent holistic labelling system of ships' environmental performance, enabling ports to differentiate their port- and fairway fees, and incentivizing cargo-owners to choose more sustainable alternatives. It is primarily applied to cargo ships, and mostly in Swedish ports, but also in a few ports in Finland and Canada.
- *Environmental Ship Index (ESI*)[249]: Managed by the International Association of Ports and Harbours, the ESI identifies ships that perform better in reducing air emissions than required by IMO. Ten Nordic ports use the ESI: five in Norway, two in Sweden, two in Denmark and one in Finland.
- *Nordic Ports for a Sustainable Future*[250]: Ten Nordic ports have signed a document acknowledging the need for collaborative actions related to energy use and alternative energy sources, including:
    - Technologies for reducing emissions to air and water, from terminal operations and ships.
    - Share knowledge and insights on innovations by connecting science, industry and startups.

The ports that signed the agreement include one Danish-Swedish port (Copenhagen-Malmö), three Swedish ports (Helsingborg, Gothenburg, Stockholm), two Danish ports (Esbjerg, Aarhus), one port in Norway (Oslo), in Finland (Helsinki), in Iceland (Faxaport), and Torshavn port in Faroe Islands.

- *Zero Emission Ports North Sea*[251]: Sweden and Denmark participated in this EU Interreg project, finalised in 2023. It aimed at facilitating the use of zero-emission fuels (electric and H_2) in the North Sea Region ports and maritime sector. For example, it addressed integration of zero-emission fuels into the port refuelling infrastructure and local energy systems, including a case study for the Danish Island Ærø.

8 Digitalisation, carbon capture, offshore wind and arctic water

This chapter covers some adjacent technological and industrial developments that influence the maritime energy transition.

8.1 Digitalisation

The fourth industrial revolution (Industry 4.0) is expected to immensely affect maritime transport, often referred to as *Shipping 4.0*[252] and ports (*Port 4.0*[253]). Technology trends like Artificial Intelligence and Big Data Analytics will drive the shipping and port industry's digital transformation, and together with smart autonomous ships can shape a new and more interconnected maritime system[254]. Nordic countries are well prepared, as exemplified below, thus having opportunities to become frontrunners also in this segment, for example within autonomous shipping and smart ports.

8.1.1 Autonomous ships

There are various definitions and interpretations of autonomous ships, referred to as *Maritime Autonomous Surface Ships* (MASS)[255]. IMO's definition includes four levels of automation degree.

1. **Automated processes and decision support -** seafarers on board operate and control the systems.
2. **Remotely controlled ship - seafarers are available on board** to take over control and operation.
3. **Remotely controlled ship - no seafarers on board**
4. **Fully autonomous ship - the** system is able to make decisions by itself

In 2017, the Danish Maritime Authority highlighted a need for global regulations on autonomous shipping. Denmark, and Norway, have largely contributed to IMO's guidelines, and the coming MASS code[256].

Already in 2016, the *Norwegian Forum for Autonomous Ships* (NFAS)[257] was established, on the premises that fully or partly unmanned ships will be an important part of the future transport system, globally. In 2020, the Norwegian Research Council awarded an 8-year national research centre for autonomous shipping. One of its recent publications presents a feasibility study for an unmanned deep sea bulk ship and short sea container ship[258]. There are several ongoing projects with autonomous testing, e.g. the container vessel Yara Birkeland[259], and the fishing support vessel Eides Pioner[260]. Remota, a company established by three offshore shipping companies, develops systems for remotely controlled ship operations. Norled **has signed an intention agreement with Remota, on further developing and operation of a control centre for autonomous ferry operations**[261]**.** In a regionally founded project, an autonomous vessel for urban transport of 50 passengers will be evaluated on a dedicated test area in Haugesund[262].

In 2022, the *ShippingLab*, a Danish innovation platform[263], announced the readiness of an autonomous ferry – the harbour bus "GreenHopper". Once permitted for autonomous sailing it will operate in Aalborg.

The Swedish Transport Agency finances a project focusing on autonomous passenger ships in an urban city environment. The Ports of Stockholm[264], together with other Swedish partners, will join forces with a Norwegian ship builder, operator, and autonomous technology supplier. Sweden's Traffic Administration[265] has ordered four autonomous full-electric ferries, including auto-mooring facilities, charging stations, a simulator facility, and a remote-control centre. The ferries, with a capacity of 60 cars, will be autonomous level 2, i.e. remotely monitored, but with crew on board that can take control whenever necessary.

Research conducted at Aalto University[266], Finland, suggests that the first level autonomous vessels, with some automated processes and decision support, is expected by 2025. Finland, being one of the leaders in R&D on autonomous vessel, opened in 2017 the world's first test area for autonomous shipping. One year later, the world's first remote control trial of an existing passenger ferry in Helsinki was made. Recently, remote piloting technology was used to direct a ship from the Port of Kokkola to the fairway.

8.1.2 Smart ports

Finland, as a leading country for digital industries, is in the front of developing "smart ports", applying digitalization, automation, autonomy, and cloud-based technologies to port infrastructure[267]. In the National Transport System Plan[268] for 2021-2032, it is stated that local authorities as port owners will promote port digitalisation and prepare for increasingly automated shipping.

In Norway, nine ports are being scanned to enable a digital port infrastructure that can contribute to automating the operation and facilitate the green transition[269]. Oslo will be the first port to receive a digital 3D-model (both above and below sea). In the research project *AutoPort*[270], Norwegian stakeholders aim to develop the next generation of small-sized autonomous ports by combining Operations Research (OR) and Artificial Intelligence (AI), to automate and optimize cargo handling processes.

The EU project *Aegis*[271] (Advanced, Efficient and Green Intermodal Systems), launched as the project "where autonomous ships meet automated ports", includes some case studies on ports in Denmark and Norway.

- North Sea Container Line cooperates with Trondheim port on using small cargo shuttles for last mile distribution to rural and urban destinations.
- DFDS leads a case on linking RoRo short sea services to inland waterways.
- Two Danish ports (Aalborg and Vordingborg) examine how existing ports can use automation to facilitate transfer of cargo from truck to sea.

8.2 Carbon capture utilisation and storage (CCUS)

CCUS is considered necessary to achieve carbon neutrality by 2050. A joint statement by Nordic Prime Ministers includes more cooperation to advance sustainable CCUS for Europe[272]. The Nordic region, and the North Sea and Baltic Sea regions, have the potential to develop a full-scale CCS chain. This also includes ship transport of CO_2, from the point of capture to the point of use, or further distribution or storage.

As highlighted in *Global Status of CCS 2022*[273], to enable CCS on a large-scale globally there is a need for developing shipping, piping and storage infrastructure. DNV foresees CO_2 carriers, i.e. ships transporting liquefied CO_2, as a new ship segment with potentially several hundred ships towards 2050[274]. Onboard CCS could be a key transformational technology for shipping to achieve net-zero emissions by 2050[275].

8.2.1 Examples of Nordic CCS activities

Norway has led the way in CCS for many years, but there are today significant CCS activities also in Denmark, Iceland and Sweden. In both Norway and Denmark, there is a large potential for storing CO_2 under the North Sea in depleted oil and gas fields or in deep saline aquifers, while in Iceland there is a high potential for mineral storage of CO_2 in basalts. In Sweden and Finland, there are limited CO_2 storage possibilities, thus the captured CO_2 must be shipped to other countries[276].

The two projects *Norwegian Longship* and *Northern Lights* are developing a full-scale CCS value chain where CO_2 is captured from industrial polluters in Norway and Northern Europe and transported by ship to a purpose-built receiving terminal at Øygarden on the Norwegian west coast[277]. The Norwegian Hydrogen Strategy, launched in 2020 and followed by a road map in 2021, also includes CCS elements, given the Norwegian focus on both green and blue H_2 production. A report by Nordic Energy Research [278] provides an overview of potential Nordic strengths and synergies across the H_2 and CCS value chains.

Through the project *Ørsted Kalundborg Hub*[279], biogenic CO_2 will be captured at two heat-and-power plants in Denmark and shipped to the Northern Lights storage reservoir in the North Sea. Another Danish CCS project, GreenPort Scandinavia[280], aims to establish the Hirtshals port as collection point for CO_2 generated during biogas production in regional plants, also including Baltic Sea countries. From Hirtshals, the CO_2 will be transported by ship to be permanently stored in a depleted Danish oil reservoir.

Partly supported by the European Innovation Fund, Iceland is building the Coda Terminal – a CO_2 hub with transport and mineral storage[281]. The aim is to establish a CO_2 value chain in Northern Europe with cross-border transport of captured CO_2 to Iceland where it is stored by permanently mineralizing it underground.

In Sweden, CCS infrastructure will most likely be based on a number of CO_2 hubs located at the coast where CO_2 is collected and exported by ship. Through the *CinfraCap*[282] project, Gothenburg port aims at becoming the first such hub, ideally located near several CO_2 emission points (large refineries and waste incineration plants). CinfraCap focuses on effective and climate-smart transport of the captured CO_2. Ports of Stockholm has also started a feasibility study on becoming a CO_2 node for eastern Sweden[283].

Large-scale CCUS in Finland will require cost-effective CO_2 transport, as Finland does not have geological CO_2 storage sites[284]. The *SHARC* project[285], aims to reduce CO_2 emissions from a Finnish refinery through green and blue H_2 production, and develop a supply chain from the refinery, by ship to storage site.

8.2.2 CO_2 transport

The increased demand for CO_2 storage creates an associated need for ship transport of CO_2. Norway is in the front, with Yara being a pioneer with three CO_2 carriers transporting CO_2 from their NH_3 production[286].

The Norwegian Breeze Ship Design develops, together with Equinor, a CO_2 carrier design for direct offshore CO_2 injection. The trading area will be North-West Europe/Scandinavia with discharge locations in the North Sea[287]. The Danish Dan-Unity CO_2, the world's first CCS-specific shipping entity, will transport CO_2 from Northern Europe to the Coda terminal in Iceland[288].

8.2.3 Onboard Carbon Capture (OCC)

Wärtsilä recently launched their concept of a CCS-ready scrubber, and the first installation will be on four new container vessels[289]. As part of the scrubber installation, additional design and engineering work will be made to ensure that future retrofits for a full CCS system are already accounted for. The CCS system is currently tested at 70% capture rate and a pilot installation will take place in early 2024.

A Swedish study by Lighthouse[290] states that there are many promising technical solutions that can make the capture and separation of CO_2 on board ships more efficient. However, to make it profitable, the economic instruments controlling GHG emissions must continue to be developed. In the Norwegian competence-building project *CCShip*[291], researchers and industry cooperate on developing cost-effective OCC solutions, and understanding when it is an attractive option for recusing a ship's CO_2 emissions. In the Green Platform project *LINCCS*[292], full-scale testing of OCC systems on a 1-MW engine is performed.

At the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, case studies on the applicability of OCC for tankers, container vessels and bulk carriers show a significant emission reduction potential, however still being very costly[293]. Based on the role OCC could play as a bridging technology, it should be further developed and considered in parallel and in combination with alternative fuels. Also, even though the development of OCC and CO_2 carriers is largely independent, they are somewhat connected as port infrastructure and storage of onboard captured CO_2 can leverage the expansion of CO_2 ship transport.

8.3 Offshore wind

The project *New Offshore Wind Ports in the Nordics*[294], financed by Nordic Innovation, aims to:

- Facilitate collaboration and development of Nordic ports in Denmark, Sweden and Norway.
- Make Nordic ports ready for expanding offshore wind industry with a stronger green infrastructure and new value chains across developers, manufacturers and sub-contractors of offshore wind.
- Develop a Nordic Offshore wind alliance, to act as an innovation advisory board.

The growing offshore wind industry comes with a demand for service operation vessels (SOVs), to build and operate the wind farms. Vard Design leads several Norwegian research projects aiming at enabling zero-emission SOV operation through energy efficiency optimalisation[295] and offshore charging[296].

8.4 Arctic

An increasing number of countries and companies are seeking to exploit the economic potential of the Arctic region related to energy production, maritime transport, research and tourism. Thus, the need for expertise in technologies for Arctic conditions is growing, for example related to ship design, port development, and implementation of wind farms. This opens opportunities for Nordic countries, all having national Arctic strategies, and all seeing the need to strengthen Arctic cooperation. In the beginning of 2023, the Nordic Cooperation launched the *Arctic Co-operation Programme*[297], providing funding to innovative and sustainable projects related to current challenges in the Arctic region.

Finland's Strategy for Arctic Policy[298] describes an expertise on a broad front, including ship design and construction, ice management and data-communication. Also, Finland has significant offshore wind power potential, however requiring technical solutions suitable for Arctic conditions. *Sweden's Strategy for the Arctic region*[299] highlights the expertise of efficient ice-breaking, which can be used both to support safe operation of commercial shipping in the Arctic, and as research vessels for monitoring the marine environment. *Iceland's Arctic Policy*[300], suggests that Iceland, with its location halfway between mainland Europe and North America, has a potential for developing "arctic hubs". One example is the greenfield industrial area planned in the Dysnes harbour site[301].

The Norwegian Arctic waters account for nearly two-thirds of all shipping traffic in the region, ahead of Russia and Iceland[302]. Traffic through the Northeast Passage offers significant opportunities for Norwegian supplier industry and maritime industry. Denmark also has a special position and interest in the Arctic since both Greenland and the Faroe Islands are part of the Kingdom of Denmark. Greenland's government is working on a new Arctic strategy, expected to pave the way for an updated joint Arctic strategy[303].

9 Nordic strongholds – review

This chapter presents a brief summary of previous reports related to Nordic collaboration and strongholds, considered relevant to the maritime energy transition in the Nordic countries.

Nordic strongholds can be referred to as innovation and business opportunities where[304]:

- synergies between the countries can be found that create potential for Nordic added value, i.e. where clear benefits can be achieved through Nordic cooperation.
- the Nordic countries have the potential to be at the international forefront, and
- there is significant potential to upscale activities, e.g. collaboration with leading global initiatives.

9.1 Previous reports on Nordic strongholds

9.1.1 Sustainable Ocean Economy – Mapping of Nordic strongholds (2021)[304]

This report from Nordic Innovation describes the ocean economy in the Nordic countries, showing that the Nordics have globally leading positions particularly in:

- Ocean transport, including maritime transport, shipbuilding and port infrastructure
- Ocean energy, including advanced offshore solutions, as part of renewable energy solutions
- Ocean food, especially technology and innovations in sustainable aquaculture

Combining Nordic strongholds of common interest, three cross-cutting opportunities for Nordic cooperation were identified:

- New applications for technology and know-how
- Nordic region as a testbed
- Use of ocean data, digitalisation

The area "Ocean transport" is considered highly relevant for the Nordics, with some priority actions:

- Stimulate development and adoption of technologies to produce and store zero-emission fuels.
- Incentivise ports supporting decarbonisation through renewable energy and fuel supply chains.
- Promote transition of the global fleet to modern modes of propulsion and renewable fuels.

9.1.2 Towards a sustainable and integrated Nordic Region (2022)[305]

In this report, the Nordic Council of Ministers presents a mid-point evaluation of their action plan for 2021-2024 in relation to the 2030 Vision. From the evaluation of Nordic solutions contributing to decarbonising the transport sector, the following conclusions were drawn related to shipping:

- Fossil-free sea traffic is being pursued in Nordic shipping industry and supported by Nordic policies.
- Following COP26, Nordic governments promised to contribute to emission-free shipping corridors.
- The project Nordic Green NH_3 Powered Ships paves the way for the first NH_3-powered ship.
- The DNV-led project Nordic Roadmap for Future Fuel in Shipping is accelerating the introduction of alternative green fuels in the Nordic Region and influencing negotiations at the EU and IMO level.

9.1.3 Nordic Action for Transformation to Low-carbon Shipping (2017)[306]

This report summarises findings from a workshop arranged as part of a project commissioned by the Nordic Council of Ministers through the Nordic Working Group for Global Climate Negotiations (NOAK). The project's focus is on opportunities for Nordic countries to achieve a transition to low-carbon shipping globally, nationally and regionally. From the workshop, with participants from various Nordic stakeholders, including government administrations, NGOs, industry and academia, the following was concluded:

- Technical and financial options are available for the Nordics to support or lead a transition.
- Opportunities exist for Nordic countries to support and lead development of public policies, needed for the transitions, both internationally and within the Nordic.

- Nordic countries can catalyse the transition by including market-based measures in the Nordic countries, setting low-carbon targets for Nordic fleets, and showcasing innovative Nordic practices.
- The success depends on including all relevant stakeholders, coordinating policies, and a holistic view of shipping and the important roles of governments, businesses and civil society.

9.1.4 Nordic clean energy scenarios – Solutions for Carbon Neutrality (2021)[307]

In this report from Nordic Energy Research, the focus is on how the Nordic countries can realise the transition towards carbon neutrality. The following main messages on Nordic collaborations were given:

- Strengthen joint Nordic action plans for infrastructure needs and development.
- Develop a joint Nordic roadmap for the role of PtX, including promising Nordic production sites.
- Develop a joint Nordic CCS strategy to realise economies of scale in carbon transport and storage.

9.1.5 Policy recommendations for the future Nordic green marine transport (2017)[308]

As a part of the Nordic Marina Project, this report presents issues raised by stakeholders in various maritime-related Nordic industries, and reflects on possible policy actions (see Table 2) to encourage adoption and further development of alternative fuels and technology. The report also includes an overview of the Nordic governments' policies and actions for promoting alternative maritime fuels.

Table 2: Example of possible policy actions towards a Nordic green maritime transport[308]

Sector	Possible policy actions
Government contribution	Long-term policy enabling transition to low-carbon fuels. Direct involvement in supporting infrastructure build-up. Implement green public procurement practices. Policy instruments that promote innovation and competitiveness of green fuels. Regulating port emissions – e.g. discounted port fees for low-emission ships.
State of technology	Develop sound business cases for the investment in infrastructure. Support accelerated standardisation of alternative fuels and technologies.
Financing and investment	Introduction of tax incentives for early adopters of alternative fuels/technology. Increase funding to commercialise research and promote green investments. Policy framework for market development of alternative fuels and infrastructure.
Research & Development	Promote/establish local, national and regional platforms for stakeholders. Fund academic networks to strengthen collaboration and information sharing.

9.1.6 Nordic Strengths in Green Transport (2017)[309]

This report includes a mapping of the Nordic countries' strengths within green transition of the transport sector to help public and private stakeholders in identifying cooperation opportunities. As the countries have different priorities and strengths, there is a need to identify areas with potential for complementarity of competences and/or for reaching a larger critical mass and mutually strengthen the Nordics.

The common Nordic strengths are ambitious climate plans, public awareness of environmental issues with transport, high innovation performance, and an emerging strength related to H_2-based solutions.

However, from the mapping of existing country-specific key strengths, only Norway and Iceland are mentioned in relation to maritime transport. Norway, for its long experience with green solutions, specifically for ferries and fisheries, and Iceland for its marine energy saving solutions. Looking at emerging strengths, Iceland is highlighted for its electrical ferries and Finland for development of green ship technologies. However, in the general characterisation of each country's transport sector, Norway and Denmark are the ones with a strong maritime segment. From the mapping of cross-Nordic strengths and good practices of cross-Nordic collaborations, only electric ferries are mentioned.

9.1.7 Hydrogen, electro-fuels, CCU and CCS in a Nordic context (2022)[278]

All Nordic countries are developing or implementing their own national H_2 strategies and roadmaps, while also exploring renewable H_2, electro-fuels and associated carbon capture technology solutions. This report, founded by Nordic Committee of Senior Officials for Energy Policies, focuses on identifying Nordic strengths and synergies in the value chain for H_2, electro-fuels and CCS/CCU.

For the maritime sector, the following remarks and recommendation were given:

- Most Nordic countries see a potential to use H_2 as fuel in short-distance shipping, however, with the precondition of a H_2 supply infrastructure in major ports.
- There is a large potential for climate benefits using electro-fuels for coastal and medium range shipping, and also within the large Danish and Norwegian long-distance shipping sector.
- In addition to climate strategies there are specific national strategies for H_2, e-fuels and CCUS.
- Considerable investments in R&D, and financial support for market introduction to early adopters.
- High availability of natural resources and renewable energy for H_2 production and carbon storage.
- The comparative strength in infrastructure development should be explored, e.g. develop a Nordic port infrastructure for H_2 distribution with direct access to international markets via ocean freight.
- On carbon storage, the Nordic countries already benefit from cross-Nordic collaboration.
- E-fuel production using captured CO_2 from biomass could enable cross-Nordic CCU, where biomass-intensive Sweden and Finland cooperate with renewable-energy-intensive Denmark and Norway.
- The Nordic countries are able to interlink feedstock, power availability, production facilities and the users of H_2 and e-fuels, which is important in supporting a H_2-based economy.

9.1.8 Hydrogen Value Chains in the Nordic (2021)[310]

In conjunction with an event arranged by Maritime Cleantech, it was concluded that each Nordic country's H_2 industry slightly differs, due to different industrial structures and technological expertise areas:

- Norway: maritime focus, with leading technology providers across blue and green H_2 value chains.
- Denmark: combines its leading position in wind industry with H_2 production for use in transport.
- Sweden: focus on use of H_2 in heavy industries (e.g. steel) but also in the heavy trucks industry.
- Finland: H_2 production mainly for chemicals and fuels, but also focuses on storage and transport.
- Iceland: for two decades H_2 has been in focus for fuel decarbonisation of the transport sector.

9.1.9 Cleaner Maritime Shipping – Lessons from Nordic Region (2020)[311]

This report provides an overview of low-emission technology options that are currently available, status of their adoption, and government plans for future development. It also includes an analysis of the regulatory frameworks in the Nordic maritime sector, including a policy review ranging from high-level national climate goals to targeted pricing measures, incentives and regulatory instruments.

The report concludes that the Nordic countries are playing a pivotal role in the following areas:

- Adoption of low-carbon technologies through demonstration, pilot and research projects, which help to overcome technical barriers and accelerate the regulatory and safety legislation.
- Contribution to IMO's work, e.g. Denmark's and Norway's input to the EEXI and CII, and Norway's important role in the IGF Code development on using low-flashpoint fuels (such as LNG).
- Acceleration of short sea electrification and provision of onshore power supply, by setting global definitions for power requirements and global standardisation of facilities/components.
- Inspiration to other countries on using financial instruments such as differentiated port pricing, tax exemptions for shore power, and environmental requirements in government procurements.

9.2 First movers

As stated in the Industry Transition Strategy, developed by Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, first-movers are critically important[312]. The Getting to Zero Coalition, an industry-led platform for stakeholders from across the global maritime value chains, has performed a mapping and analysis of first movers in the shipping industry[313]. It concludes that first-movers have clearly shown their willingness and ability to use green technology, but it has to be scaled up. Norway is highlighted as a strong first-mover:

- Norway led the most recent fuel transition (LNG) and electrification and is in a unique position to facilitate the spread of any fuel transition if done in collaboration with the rest of the region.
- The transition to LNG is a "success story" having high importance on maritime energy transition. Here, the Norwegian government-controlled domestic ferry industry acted as a testbed, and the NOx Fund supported financing for LNG vessels operating in Norwegian territorial waters.
- The NOx Fund also supported the first LNG ships in Sweden (chemical tankers) and Denmark (cruise ferry). These ships then acted as proof of concept to shipowners not eligible for the NOx Fund.
- Nordic LNG ships also benefitted from early establishment of bunkering infrastructure in Norway, and from Norway's leading role in development of IMO rules for LNG-fuelled ships (IGF Code).

Support to first movers is considered a key action in the transition towards zero-carbon shipping, and it is suggested that countries act in parallel or in a more coordinated way. A key takeaway from the first Nordic Roadmap conference[314] was that the Nordics can be a first-mover region, leading the way in this transition. The Getting to Zero Coalition continuously updates a mapping of zero-emission projects, including demonstration and pilot projects on ship technology, fuel production, and bunkering infrastructure[315]. Project details are found on *NextGEN*[316], a website hosted by IMO to facilitate global collaboration. The mapping shows 70 projects in Norway, 38 in Denmark, 29 in Sweden and 21 in Finland.

10 Political missions and declarations

10.1 Nordic Ministerial Declaration

In 2022, all Nordic Ministers for Environment and Climate approved a *Declaration on zero emission shipping routes between Nordic countries*. The declaration includes the following statements[317]:

- Recall the vision of Nordic cooperation becoming the world's most sustainable, integrated region.
- Recognize the need to undertake major efforts to accelerate decarbonisation of Nordic shipping.
- Recall the COP 26 Declaration on Zero Emission Shipping by 2050, to strengthen global efforts.
- Recall the Clydebank Declaration, supporting establishment of at least 6 green corridors, by 2050.
- Agree that global availability of clean maritime fuels, zero-emission vessels, alternative propulsion systems, and landside infrastructure to support these, is imperative for a rapid green transition.
- Agree also on the benefits of Nordic cooperation taking a leading role in transitioning the shipping sector, e.g. through supporting decarbonising most of the Nordic ferry transport by 2030.
- Agree to support establishment of zero emission routes for ferry transport in the Nordics.
- *Decide* to establish a pilot project for identifying such routes and interested actors from the shipping industry to enter into partnerships on realizing zero emission shipping on these routes.

10.2 Mission Innovation

Mission Innovation is a multilateral initiative on clean energy innovation. One of the missions is *Zero-Emission Shipping*[318], being co-led by Denmark, the US and Norway along with the Global Maritime Forum and Mærsk Mc-Kinney Møller Center. The goal is to demonstrate commercially viable zero-emission ships by 2030. To achieve this, coordinated innovation needs to take place across the entire maritime value chain.

The *Industry Roadmap*[319] identified 120 innovation gaps and concluded that innovation is required to:

- accelerate the market readiness of zero-emission ship technologies.
- stimulate development of a multi-fuel mix, suitable for different modes and areas of operation,
- address systemic gaps affecting all fuel types,
- develop, demonstrate and deploy zero-emission ships, fuels, and infrastructure, simultaneously.

In the *Action Plan*[320], 43 prioritized actions were identified, divided into five main categories:

- Safety and operational risk management: procedures for safe fuel handling or storage
- Policy and regulation: national and international policy informing regulations or market incentives.
- Market and business development: business models, economic modelling, funding mechanisms.
- Technology development and adaption: R&D on engines, fuel cells, integration, life-cycle emissions.
- Market analysis: sharing of knowledge and best practice, e.g. fuel availability/infrastructure.

10.3 Green Voyage

The project *GreenVoyage2050*[321] is a partnership between the Norwegian Government and IMO. The main goal is to support developing countries in their efforts to reduce GHG emissions, for example by:

- Devloping tools to support implementation of IMO's GHG strategy
- Devloping policies and national action plans, as well as strategic partnerships
- Cooperation on technology development, innovation, pilots and demonstrations

10.4 Green Shipping Challenge

Ahead of COP27, the US and Norway launched the *Green Shipping Challenge* (GSC)[322], urging stakeholders to give commitments for decarbonising the sector by 2050. Except from Iceland, all Nordic countries are

GSC participants, implying that they must make at least one major announcement to spur the green transition. The following announcements are made by the Nordic countries or involves a Nordic country.

10.4.1 Denmark

Catalyst for change - from local to global green shipping. Denmark will contribute to develop international green corridors and zero-emission shipping through four interlinked elements:

- Nordic vision on green ferry routes by 2030, and Clydebank declaration on green corridors.
- Development of a national action plan for Danish green corridors.
- Participation in the Nordic Roadmap project (introduction of sustainable zero-carbon fuels).
- Support the Zero-Emission Shipping Mission's "Blueprint for Future Ports program", which will develop a blueprint for fully operational and commercially ready zero-emission ports in the 2030s.

Mærsk Mc-Kinney Møller Center: Blueprint for Green Corridors Pre-Feasibility Studies. The blueprint provides a ready-to-use guide for project stakeholders interested in understanding the green corridor options in a given region, and to make holistic value-chain assessments.

A.P. Moller Maersk and the Spanish Government have signed a General Protocol for Collaboration to explore the opportunities for large-scale green fuels production in Spain.

10.4.2 Finland

Fintraffic Vessel Services: Port Activity App boosts the efficiency of the entire logistics chain. The Port Activity App is a new user interface for port digitalisation communication, with the purpose to strengthen collaboration both inside the port community and between ports, generating a more efficient process. Further development of the App will enable calculations of GHG emissions in the maritime logistics chain.

Siili Solutions, Fintraffic: Virtual Port Arrival through data-focused collaboration and information sharing. In line with an EU regulation on creating a European Maritime Single Window, through which vessel port notification and information is harmonized across the EU, Finland is creating a national neutral data platform between key stakeholders that will optimize digitalisation, such as Virtual Port Arrival.

Meriaura, Green NorthH_2, Wärtsilä: Cargo Vessel operated on green NH_3, including e-fuel production. The consortium aims for an NH_3-ready vessel trading in short-sea market in 2024. At delivery, it will operate on LBG, but from 2026 in combination with renewable NH_3. By 2030, the target is to offer zero-emission concepts, supported by maturing fuel technology, infrastructure, and regulatory framework.

Rauma Marine, Viking Line, Kempower: Scalable green corridor based on local renewable fuel production. Operating on locally produced renewable fuel can give competitive advantage by eliminating emissions in logistics. By scaling the concept, emissions from RoPax ships in Northern Europe can be halved by 2035, while also establishing local renewable fuel production supporting local economies.

10.4.3 Norway

Green Shipping Programme (GSP) – NH_3. With the combined efforts of more than 100 partners, the GSP contributes to developing and deploying NH_3 as a maritime fuel. This includes four NH_3 pilot studies by 2023, and realization of three NH_3-powered ships and one NH_3-based green corridor by 2026.

Enhanced domestic actions towards zero emission shipping. By COP28, the national action plan for green shipping will be updated on climate requirements, use of carbon pricing, climate support schemes and private-public partnerships, as well as a plan for upscaling sustainable fuel production and infrastructure. A "barometer" will be developed, for updates on green ships in operation and order, and annual emissions.

Enhanced international actions towards zero emission shipping. Strengthen global efforts to decarbonise shipping, especially at IMO to establish an ambition for zero-emission international shipping by 2050, and to adopt measures like carbon pricing. Further support developing countries on the transition to zero-emission shipping and work together with Nordic countries to establish a Nordic green shipping corridor.

Norwegian Maritime Partners: Cooperation obligation towards zero emission shipping. To reach the 2030 goals, 700 low-emission and 400 zero-emission Norwegian ships are needed. To realize this, cooperation between maritime industry, shipping associations, classification and finance must be strengthened.

Int. Chamber of Shipping, Int. Association of Ports and Harbors: Clean Energy Marine Hubs. The hub will provide a, first of its kind, public-private platform bringing together stakeholders across the energy- and maritime value chain to partner with governments aiming to produce, transport and use low-carbon ship fuels. Five countries, among them Norway, are the first to share knowledge and best practices on how to accelerate the establishment of clean energy hubs close to ports.

UK bilateral green shipping corridors agreements with the US, Norway, and the Netherlands. Building on the COP26 legacy of the Clydebank Declaration, the UK has announced commitments with Norway, the US, and the Netherlands to support establishment of green shipping corridors between the countries.

10.4.4 Sweden

Port of Gothenburg, Stena Line, DFDS, Ørsted, Liquid Wind – Europe's first hub for green e-fuels. This industry-wide collaboration aims to establish an e-fuel bunker hub in the port, starting with e-methanol.

Green Corridor between Sweden and the Netherlands. The Port of Gothenburg and the Port of Rotterdam have signed an MoU for realization of a green shipping corridor, based on e-methanol. This will also strengthen the ports' ongoing cooperation on carbon reduction and digitalisation.

Green Corridor between Sweden and Belgium. This green corridor, also aiming for e-methanol, between Port of Gothenburg and the North Sea Port in Ghent, is at a very advanced stage. It is already considered to extend the project to the whole logistic chain, in particular onshore activities.

10.4.5 Others

Of the total 44 announcements, the following two "non-Nordic" ones are considered especially relevant:

Joint Statement on Green H_2 for Shipping. Ten organizations, including green H_2 producers and green shipping leaders, have jointly committed to produce and deploy the significant volumes needed for full decarbonisation by 2050, and are calling on policymakers to help achieve the ambitious targets.

Lloyd's Register (LR): Framework on Zero Carbon Readiness. "Readiness" needs to be clarified, since it can mean anything from a ship being fully equipped to bunker alternative fuel today, to a vessel that could be converted in the future – potentially requiring a major retrofit with significant safety implications and costs. There will be a call for commitments from across the industry to apply the "readiness" framework.

11 Strongholds and challenges for the Nordics

11.1 Assessing innovation system dynamics: a functions approach

Here, we summarize key insights from previous chapters in a sectoral innovation systems (SIS) perspective. In doing so, we also add results from a survey among maritime sector stakeholders undertaken in MAREN, as well as recent research, workshops and discussions within the MAREN consortium.

The SIS perspective forms part of a broader family of innovation systems approaches (cf. national, regional, technological) that have been widely applied over the last 2-3 decades in various social science fields. A SIS is seen to be constituted by a set of products (or technologies, infrastructures) and agents "carrying out market and non-market interactions for the creation, production and sale of those products"[323]. Agents are both individuals and organisations, whose interactions are shaped by both formal (i.e. rules, regulations) and informal (i.e. norms, values) institutions. A first step in innovation system analysis is often to map the structure of technologies (i.e. products), actors (incl. networks), and institutions.

Given our aim to articulate a set of recommendations for a Nordic strategy on maritime energy transitions, we follow a functions approach which is suggested to improve sectoral technology roadmaps[324]. The system functions approach is an oft-used framework to assess the strengths and weaknesses of innovation systems[325]. A key argument is that mapping the structure of an innovation system does not say much about whether or not the system is performing well in terms of facilitating/supporting innovation, and ultimately contributes to desired changes such as reducing the environmental footprint of a sector. To assess innovation system performance, the functions framework analytically distinguishes a set of resource formation processes (i.e. functions) considered necessary for technological innovation processes to gain momentum. A functions approach was, for example, employed in a research study analysing the development of battery-electric and H_2 solutions for maritime transport in Norway[326].

Innovation is here understood in a broad sense, spanning from early R&D via experimentation and piloting to upscaling and market diffusion. In the context of environmental innovation, the latter is obviously crucial to enable the necessary transformation towards more sustainable production and consumption systems. A key dynamic emphasized by innovation scholars is that considerable innovation tends to occur post market-entry via learning by doing in user-producer interaction. Most of this innovation tends to be relatively incremental and helps to optimize, increase efficiency, and reduce cost, but radical innovation can also occur after a technology has gained a foothold in a market. This can be at the component or sub-system level, but also at the interface between different technical systems (e.g. charging interfaces for electric mobility).

The functions approach typically includes 6-8 functions. Here we organise our insights according to the following functions, and our operationalisation is mainly based on the study by Bergek et al.[325]

- <u>Entrepreneurial experimentation</u>: this function refers to the development and testing of new solutions (or combinations of them), many of which will often fail whereas others will succeed. It is considered crucial for exploring new options and reducing uncertainties.
  - Examples of indicators: number and type of new entrants, diversification activities, number and extent of experimentation with new solutions

- <u>Knowledge development and diffusion</u>: this function refers to the knowledge base of a sector and relevant technologies. It incorporates different types of knowledge (e.g. scientific, technical, production, market) and diffuses in different ways (learning through R&D, imitation, or in user-producer relations).
  - Examples of indicators: number of R&D projects, patents, scientific publications, conferences

- Direction of search: this refers to various incentives and/or pressures that induce actors to direct their attention and resource use to, in this case, solutions for decarbonising the maritime sector. The function includes visions and expectations, perceptions of opportunities, articulation of demand, regulations and policy, and also particular problems or bottlenecks that need to be solved.
  - Examples of indicators: expectations related to growth potential, incentives in the form of taxes, regulatory pressure, articulation of demand (from different types of customers)

- Market formation: for new technologies to develop and upscale, the development of well-functioning markets is essential. Market formation often occurs through a set of steps, beginning with an early niche or 'nursing market' where new solutions get tested in real-world operating conditions, followed by a 'bridging market' with technological diffusion (e.g. to other user groups or segments), and finally (and only possibly) the formation of a 'mass market' with more or less standardised products.
  - Examples of indicators: users/customers and their demand articulation, institutional support (e.g. regulatory) for market formation, market size.

- Resource mobilization: different resources need to be mobilized for new technologies to develop and diffuse successfully, and these will typically vary with importance during various development phases. Most often, resource mobilisation incorporates competence/human capital, financial capital, and complementary assets. An example of the latter in the context of maritime decarbonisation is new materials to reduce the weight of ships, or digital technologies that can help improve energy efficiency.
  - Examples of indicators: volumes of investment, availability of venture and seed capital, and necessary human capital (including skilled personnel), development of complementary assets.

- Legitimation: this refers to compliance with regulations and standards (i.e. formal institutions), social acceptance, and acceptance among potential technology adopters (i.e. informal institutions). New solutions must be perceived as appropriate and able to meet necessary needs, e.g. power demand.
  - Examples of indicators: perceptions of legitimacy among technology adopters, acceptance in general public and with policy makers, alignment with policies and institutions.

These functions are interconnected and must be analytically delineated. For example, experimentation leads to knowledge development, often involving resource mobilization. Successful experimentation may bolster legitimacy and incentivize (direction of search) more actors to enter the technological field. Conversely, feedback effects may also be negative, for example if insufficient legitimacy hampers market formation.

The empirical scope of innovation system analysis is usually a sector or technology within a region or country. The present analysis is somewhat unconventional in that the scope is one sector (albeit broad) across several countries, and multiple technological solutions. This comes with a limitation in that the assessment is necessarily relatively broad-based. Given the variety of opportunities for maritime decarbonisation, as described in this report, however, we consider a comprehensive view on the strengths and weaknesses of the Nordic maritime sector's innovation system with regards to low- and zero-carbon solutions as appropriate. Note that the assessment of strengths and weaknesses is related to the innovation systems' momentum with regards to supporting the shift to low- and zero-carbon (LoZeC) fuels and energy carriers.

11.2 The Nordic maritime innovation system: strengths and weaknesses

11.2.1 Innovation system assessment: structure

As seen in section 3, the Nordic maritime sector is large and serves key roles in transporting goods and passengers, as well as being central to several sectors such as offshore energy, fishing and aquaculture. While there are obviously substantial differences between the Nordic countries in terms of fleet composition and size, we here assess the maritime sector innovation system in the Nordics as a whole. We do however comment on country differences, and also specify according to technologies, where relevant.

Previous sections substantiate that the Nordics are relatively advanced in innovation and transformation of the maritime sector. A broad range of established and entrepreneurial firms are involved in the development and implementation of solutions that allow for decarbonisation, including both technology users (i.e. shipowners) and suppliers (i.e. technology firms). The latter includes not only "traditional" maritime sector suppliers, but also companies from, for instance, the ICT or power technology sectors. The SIS also includes non-firm actors, like universities, R&D institutes, classification societies, public agencies and governmental departments. Combined, the Nordic maritime innovation system is in structural terms clearly strong.

11.2.2 Innovation system assessment: functions

Entrepreneurial experimentation

As shown in this report, there is substantial experimentation with new energy solutions within the Nordic maritime sector. This includes not only development and testing of new solutions on different vessel types, but also in ports and on the supply side, including new bunkering solutions and integrated energy hubs. A significant part of the experimental activities was enabled by various national-level and EU funding schemes. Experimentation furthermore involves a broad set of actors, including many of the large existing technology suppliers, shipping companies, and a varied set of start-ups and other new entrants to the maritime sector.

The MAREN team identified a number of areas in which there is a need for further experimentation. These include flexibility solutions in fuel production and provision, as well as experimentation with smart energy grid solutions and energy system integration that consider interfaces between maritime shipping, onshore energy sectors, and other energy end-use sectors. There is also a need for large-scale demonstration of novel charging and bunkering facilities for different types of ships. Another aspect is the need for experimentation on relevance to retrofitting, given that almost all existing ships, and also most ships that are currently on order or being built, are equipped with conventional machinery.

Participants also pointed to the need for not solely focusing on novel fuels, but also on complementary experimentation with operational measures, as well as wind propulsion and onboard carbon capture.

❖ Given the substantial entrepreneurial experimentation within the Nordic maritime sector, we assess this innovation system function to be strong, albeit with need for improvement.

Knowledge development and diffusion

The findings in this report reflect a strong knowledge base in existing Nordic maritime and energy sectors, and in related research and education. One relevant indicator is the number of scientific publications on 'green shipping', as shown in Figure 10, which has been rising quite steadily over the last decade and more.

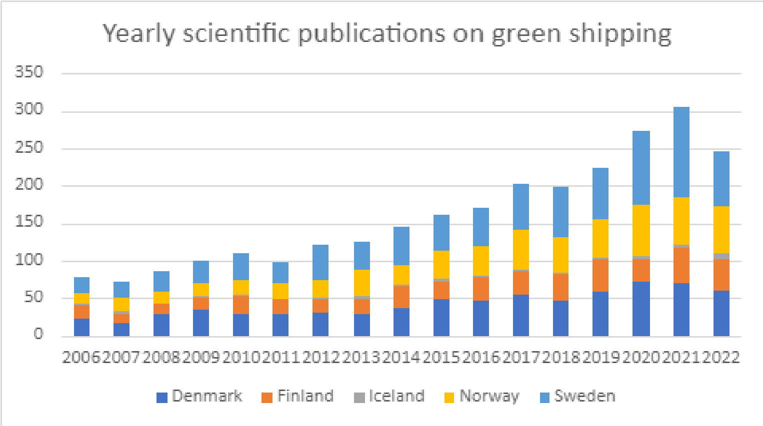

Figure 10 Scientific publication overview in the Nordics 2006-2022[a]

MAREN participants also pointed to the need for knowledge development in public agencies and authorities with regards to LoZeCs, both with regards to technical issues and regulations/legal matters. In general, there is furthermore a need for updating all levels of education and training of the maritime sector workforce, with regards to sustainability, LoZeC fuels, and other measures to reduce emissions.

❖ While there is an overall positive development in the knowledge development and diffusion function, there are also several shortcomings and gaps that currently hinder decarbonisation processes. We therefore assess this function as being moderate.

Direction of search

There is clearly an increasing recognition within the maritime sector that decarbonisation must be achieved, and, as this report shows, there are increasing efforts in the Nordics to develop new energy solutions. As is typical in periods of transformation, a relatively low number of industrial actors will be pioneers or early movers, whereas most will be followers and laggards[2]. While there are many positive developments, there still exists a resistance to change (conservatism) in the maritime sector, as also shown in several research studies[327] [328], which needs to be acknowledged with regards to policy development.

Policy targets are key incentives, but while policy makers have set ambitious targets, these are somewhat unclear and hitherto not followed up in terms of a sufficiently comprehensive set of policy instruments (carrots and sticks). This, combined with the fact that there is substantial uncertainty with regards to which fuels and energy carriers that will materialise upscale (cf. Section 4), means that the business case is in many circumstances far from clear both for shipping companies, ports and fuel producers.

Ship segments with public procurement (e.g. ferries in Norway) and relatively long-term contracts are prime examples of sectors where technological substitution is both technically feasible and strongly supported by adequate policy instruments. However, many shipping segments are dominated by short-term contracts and price-based (spot market) competition, with no or limited premiums for low-emission operation.

[a] Search string: (TI=("*marine propulsion*" OR *marine vessel* OR *marine engine* OR *ship* OR *boat* OR *shipping*) OR TS=("*marine propulsion*" OR *marine vessel* OR *marine engine* OR *ship* OR *boat* OR *shipping*)) AND (TI =(*iogas*) OR TS=(*iogas*) OR TI =("*ynthetic natural gas*" OR "*SNG*") OR TS=("*ynthetic natural gas*" OR "*SNG*") OR TI =(*iodiesel*) OR TS=(*iodiesel*) OR TI =(*ioethanol*) OR TS=(*ioethanol*) OR TI =("*fuel cell*") OR TS=("*fuel cell*") OR TI=("*electricity storage" OR "*battery*") OR TS=("*electricity storage" OR "*battery*") OR TI=(*ammonia*) OR TS=(*ammonia*) OR TI=(*e-fuel*) OR TS=(*e-fuel*) OR TI=(*methanol*) OR TS=(*methanol*) OR TI=(*methanol*) OR TS=(*methanol*) OR TI=(*hydrogen*) OR TS=(*hydrogen*) OR TI=("*wind-assisted*" OR "*wind assisted*" OR "*wasp*" OR "*waps*") OR TS=("*wind-assisted*" OR "*wind assisted*" OR "*wasp*" OR "*waps*"))

- ❖ The direction of search innovation system function is assessed to be moderate. That is, while the long-term goal is relatively clear (i.e. need to decarbonise), the pathways moving forward are unclear while incentives to decarbonise are often lacking or not sufficiently strong.

Market formation

Early market formation for LoZeC fuels has been strong, particularly in Norway, and especially in specific segments such as ferries and offshore supply vessels[326]. Apart from LNG and some uptake of biofuels, this has however been limited primarily to battery-electric systems. While there is increasing diffusion of novel energy solutions in Nordic shipping (cf. Sections 5 and 6), and various actors (including ports) announce plans or ambitions to provide fuels (cf. Section 7), it is fair to say that current development is slow.

Partly, this can be attributed to conservatism in the maritime sector, which is understandable given factors such as the longevity of investments, risks associated with new energy solutions and so forth. On the other hand, limited demand obviously mirrors limited supply (and cost uncertainties), implying a current lack of sufficiently strong positive feedback effects that can help stimulate the development of novel energy value chains[2]. A general challenge is the heterogeneity both among energy end-users in the maritime sector, and in value chains that must be established to produce and distribute various LoZeC fuels[329]. Another challenge is that much of the maritime sector competes internationally, and also with other modes of transport.

- ❖ Overall, we consider the market formation function to be weak. While there are positive developments in some distinct market segments, market uptake of low- and zero-carbon fuels is limited.

Resource mobilisation

As already mentioned there has been a strong increase in available funding for early phase (experimentation, R&D) innovation activities within multiple areas of relevance to the maritime transition. Particularly in Norway there has also been investment support that has allowed for diffusion especially of OPS and onboard battery-electric systems. In general, however, high investment costs associated with novel energy solutions are a general barrier for shipowners within many, if not most, shipping segments. The same applies for shore-side infrastructure such as charging equipment and bunkering.

A sustainable transformation of the maritime sector is clearly encumbered by chicken-and-egg problems, that is, the lack of supply hindering growth in demand and vice versa[2]. Current limited security of supply of novel fuels is thus a key barrier that needs to be dealt with. There are also typically both technical and institutional challenges in the various interfaces between different sectors (e.g. the charging interface between the electricity grid and maritime sector) that need to be resolved[330] .

On a more positive note, there are multiple developments in this regard, with a high number of announced plans to invest in production facilities for LoZeC. There are also positive developments related to other infrastructure investments, such as floating charging, energy islands and multi-fuel bunkering hubs. We also witness a large potential in ports for sector coupling, thereby allowing ports to develop a role as energy hubs that offer a diversity of fuels. The EU's and Nordic's push for 'green corridors' may as such prove highly important in terms of facilitating coordinated investments in novel physical infrastructure for LoZeCs.

Availability of the necessary human resources is however a concern, as noted also for the knowledge development and diffusion function. That is, decarbonisation requires not only new technical competencies in the maritime sector, but also skills related to ship design and building, operations, regulations, HSE and commercial aspects. However, as noted by MAREN participants, there is much to learn from other sectors regarding for example the safe handling of novel fuels and energy carriers.

- ❖ Despite positive developments, we assess the resource mobilisation to be weak. Significant investments will be needed, in shipping companies, ports and energy value chains, to allow for decarbonisation, and this development remains too slow. There are also concerns related to availability of human capital.

Legitimation

This report reflects a general sentiment that emission reductions are needed in the maritime sector. Overall, this contributes to legitimation of novel energy solutions, although most are in relatively early stages of development. Nonetheless, there is scepticism associated with LoZeC fuels and energy carriers (security of supply, costs, safety etc.), meaning that the legitimation function is not strong. Novel energy solutions come not only with high investment costs but also new types of risks. For most technology adopters, it is particularly important that new solutions have been demonstrated to be safe, reliable and cost-competitive. Many of the LoZeC fuels that are foreseen to be important are yet quite far from this level of maturity.

Furthermore, there has been and, in many instances, remains a lack of sufficient regulations and standards for energy solutions and carriers, both onboard ships, in ports, and for distribution. There is also considerable uncertainty regarding well-to-tank emissions (i.e. the overall sustainability) of novel fuels (e.g. biofuels), and societal-level concerns related to energy use. These can relate to conflicts over land-use to produce fuels, as well as development of necessary energy infrastructure (e.g. bunkering) of certain fuels in, or close to, ports.

❖ We assess the legitimation function to be moderate. That is, while the need to decarbonise is becoming increasingly recognized, there is considerable uncertainty on many dimensions that hinder increased diffusion of low- and zero-carbon energy solutions.

Overall assessment

The overall assessment (see Table 3) is that the Nordic maritime sectoral innovation system is strong when it comes to experimentation with new solutions. We consider the knowledge development and diffusion, direction of search and legitimation to be moderate, while market formation and resource mobilisation are assessed to be weak. This assessment reflects that the transition to LoZeC energy solutions and fuels in the maritime sector is in an early phase of development and is likely to take several decades. In this phase, experimenting with new solutions, developing the knowledge base, incentivizing diverse actors to direct their attention towards (in this case) novel energy solutions and enhancing the legitimation of both decarbonisation in general and specific solutions can be considered both 'natural' and positive. On the other hand, strong performance of the market formation and resource mobilisation functions would be indicative of stronger momentum for decarbonisation as reflected in investments. Thus, while there are certainly positive developments, the challenge is that the decarbonisation is urgent[330], also for the maritime sector.

Table 3: Assessment of functions related to Nordic maritime innovation systems.

Function	**Assessment**
Entrepreneurial experimentation	Strong
Knowledge development and diffusion	Moderate
Direction of search	Moderate
Market formation	Weak
Resource mobilisation	Weak
Legitimation	Moderate

There are clear differences, both between various decarbonisation solutions, as well as between countries. Concerning technologies, battery-electric systems have matured considerably and diffused relatively fast, especially in Norway. Many ports have implemented OPS (also high voltage) and many more have announced ambitions to do so. Whilst this is highly positive, as it allows for emission reductions from ports and shipping segments that operate on short and fixed routes and/or have variable power demand, there are obvious limits to the total emission reductions that can be achieved with battery-electric systems.

The LoZeC fuels needed to enable maritime decarbonisation are generally at an immature development stage. Fuels that can function as drop-in fuels in existing ship engines obviously have the advantage that 'only' the production side of the value chain needs to develop. However, this development is relatively slow and there are challenges related to resource availability (carbon, energy, biomass). Other fuels such as H_2 and NH_3 require changes along the entire value chain, including ship engine technology, while also relying on renewable power and infrastructure development for production, distribution, storage and bunkering. While there is a growing momentum both on the production and consumption side of these value chains, considerable efforts are needed for these fuels to become available and implemented.

On a country-level, there are equally substantial differences with regards to how far the countries have come on the 'maritime decarbonisation journey'. Norway has in many ways pioneered much of the energy-related technology development (LNG, batteries, and more recently also H_2), but often with involvement of other Nordic actors (e.g. technology suppliers). As this report has shown, there is also strong commitments across the Nordics, both among shipping companies and ports, to implement new solutions. Nonetheless, certain shipping segments, such as fishing, are to a large extent missing from R&D&I efforts, which is a concern.

A positive aspect influencing the feasibility of the Nordic maritime sector decarbonisation is that a high share of maritime traffic in the region is domestic and intra-Nordic, whereas much of the international traffic is to nearby countries. This allows for concerted efforts to establish the necessary energy infrastructures along key shipping routes and to harmonize standardisation of e.g. charging interfaces.

As the transition progresses, a key issue will be the availability of LoZeC fuels, mostly relying on development and upscaling of novel value chains involving multiple other sectors[2]. This challenge is however not unique to the maritime sector. In other words, moving forward there will be challenges in terms of competition over scarce resources (energy, materials) between not only transport sectors but also process industries and others[331]. This competition is in our view more likely to increase rather than decrease in the coming years and will require considerable attention from policy makers and industry actors alike to prevent backlash and resistance.

12 Recommendations

Our recommendations follow from the sectoral innovation system of the Nordic maritime sector, represented in Section 11, and also draws on recent research[329].

- Enforce stronger taxation of GHG emissions.
    - Applying the polluter pays principle benefits all alternative fuels and energy solutions.
- Use public procurement policy instruments to incentivise uptake of low- and zero-carbon energy solutions in all relevant shipping segments.
    - This applies not only to shipping segments where procurement can be applied directly, such as vessels that are part of public transport infrastructure, but also for 'green logistics'.
- Implement stricter environmental requirements in government-awarded licenses in fishing, aquaculture, and offshore energy sectors.
    - Offshore activities are granted rights to use the 'commons', and concession schemes can include GHG emission allowances.
- Support ports in collaboration efforts to harmonise fee systems and e.g. charging systems.
    - This can be done with soft instruments and facilitate more rapid diffusion of alternative fuels and energy solutions.
- Build public sector regulatory capacity for emerging technologies.
    - Lack of regulations and standards hamper the development and diffusion of alternative fuels.
- Address unresolved regulatory issues, considering complete energy value chains.
    - Several alternative energy solutions are held back due to regulatory uncertainty, and require attention from regulatory bodies and authorities across different domains and sectors.
- Acknowledge the need for technology-specific support while using sectoral- and general-level policies (e.g. GHG taxation) to the greatest extent possible
    - Alternative fuels differ considerably with regards to maturity, risks, and costs, considering a whole value-chain approach.
- Ensure holistic planning, incorporating also upstream (energy) value chain developments (and potential bottlenecks) such as renewable energy production and grid distribution capacity.
    - The novel energy value chains that need to be developed for maritime decarbonisation cut across multiple sectors.
- Increase R&D funding for alternative fuels.
    - Alternative fuels are generally in early phases of development and continued R&D efforts are needed.
- Implement policy instruments that provide 'whole value chain' support for alternative fuels
    - Alternative fuels are confronted with significant 'chicken-and-egg'-problems.
- Support the development and upscaling of processing capacity for alternative fuels, e.g. with contracts for difference.

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