International Transport Forum

Navigating Towards Cleaner Maritime Shipping

Lessons From the Nordic Region

Decarbonising Transport

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Nordic Energy Research

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International Transport Forum
2 rue André Pascal
F-75775 Paris Cedex 16
contact@itf-oecd.org
www.itf-oecd.org

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This work is part of the ITF Decarbonising Transport Initiative (DTI), a key instrument developed by the ITF to help governments and industry to translate climate ambitions into actions. The initiative brings together a partnership that extends far beyond the ITF’s member countries. Its work:

- tracks progress to evaluate how current mitigation measures contribute to reaching objectives for reducing greenhouse gas (GHG) emissions from transport
- develops in-depth sectoral and focus studies to identify effective policies in specific modes (e.g. road transport) and thematic areas (e.g. cities)
- brings policies together in a catalogue of effective measures, to support countries to develop their GHG emission mitigation strategy in transport
- supports the policy dialogue, leveraging on extensive engagement with the United Nations Framework Convention on Climate Change (UNFCCC), including the ITF’s designation as a focal point for transport of the Marrakech Partnership for Global Climate Action (MP-GCA).

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Nordic Energy Research (NER) is a regional platform for co-operative energy research and policy development under the auspices of Nordic Council of Ministers. NER is based in Oslo, together with its sister organisations Nordforsk and Nordic Innovation. Nordic co-operation in energy research started in 1975, leading to common research funding since 1985 and the establishment of NER as an institution under the Nordic Council of Ministers in 1999. The governance structure of NER is closely connected to both the national governments of the five Nordic countries as well as the intergovernmental Nordic system. NER manages numerous projects and facilitates Ministerial working groups that provide input to energy technology policy making in the region.

NER funds research that is of shared Nordic interest and that supports the region's ambition to reduce carbon emissions and dependence on fossil fuels, and to create new growth industries based on green technology. It does so by expanding knowledge on sustainable energy and contributing to the development of new and competitive energy solutions.

NER has been supporting research at the intersection of transport, energy and environment since its inception. In particular, NER funded research on electro-fuels, biofuels, fuel cells and electric transport. Projects funded by NER cover various modes of transport, including aviation, heavy freight, maritime transport, public transport and personal electric vehicles.

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What we did

This report analyses prospects for energy use in the Nordic shipping sector. It outlines potential solutions that could allow the region to pro-actively respond to the imperatives of energy diversification, the reduction of local pollutants and the abatement of greenhouse gas (GHG) emissions. As the Nordic region is pioneering efforts to reduce the environmental impact of maritime shipping, making the findings of this report relevant around the globe.

The assessment covers technologies and polices. It reviews technological options to improve the ships' energy efficiency and low-emission fuels, and outlines technical and financial barriers to their widespread adoption. Surveys of recent projects in the Nordic countries support the analysis. The policy review ranges from high-level national climate goals to targeted pricing measures, incentives and regulatory instruments. It includes an in-depth analysis of the regulatory frameworks in place in the Nordic maritime sector.

What we found

Accelerating the pace of technological development and the uptake of new technologies in the Nordic region will contribute to a successful transition to cleaner maritime shipping globally. Accelerated innovation is important in a sector dependent on long-lasting assets like ships. Policy is a critical tool to stimulate the deployment of maritime low-carbon technologies, including solutions that could be viable as retrofits Policies supporting innovations at different development stages help to complement solutions adopted in the shorter term by other technologies in later years.

Readily available technologies can unlock efficiency improvements and are an urgent priority. Payback periods for known technologies are often manageable, making them cost effective. These technologies are an essential pillar of a transition to low-carbon shipping and the competitiveness of maritime transport – notably if a switch to low-carbon fuels increases energy costs. Promising efficiency improvements include wind assistance technologies and skin friction improvements via reduced hull fouling and hull air lubrication. Other energy efficiency savings can continue to come from increases in ship capacity – provided that capacity utilisation does not decline – and slow steaming.

In addition to energy efficiency, low-carbon fuels/energy vectors are needed to decarbonise the maritime sector. Biofuels, electricity, hydrogen, synthetic hydrocarbons and ammonia are the most promising options, if produced with low-carbon energy and (where relevant) renewable carbon, when comparing energy options based on well-to-wake and lifecycle assessments.

Conversely, Liquefied Natural Gas (LNG) or methanol (when produced using fossil fuels) do not deliver, in current conditions, significantly lower GHG emissions than conventional marine fuels. Current policies focus on direct CO_2 emissions and do not account for other GHG emissions such as methane or emissions from upstream fuel production. This limitation creates inappropriate advantages for fuels such as fossil LNG, as its main benefit of relatively low direct CO_2 emissions is offset by relatively high well-to-wake GHG emissions.

Electric ships can be highly effective at reducing ship emissions for short distance routes. They are an area of innovation in which the Nordic region is leading. The low energy density of batteries limits the potential of fully electric ships for long distance journeys, however. Compressed hydrogen also requires large storage volumes that make it less suitable for powering vessels for transoceanic travel.

The use of onshore power can help to reduce marine oil consumption and alleviate air pollution in ports. Importantly, it could provide the charging infrastructure for ship batteries and thus the foundation for the electrification of maritime transport. That said, the wide range of systems used to charge ships places burdens on the regulatory approval of new vessels, which poses one of the barriers to the large-scale adoption of shore power.

Advanced biofuels can play a significant role in reducing petroleum-based fuel demand and GHG emissions, in particular liquids that can use existing fuel infrastructure. However, biofuel use in the maritime sector will likely compete with other transport modes and sectors. This also applies to synthetic fuels requiring renewable electricity for their production. Clear sustainability criteria are needed for advanced biofuels, including on land use and direct and indirect land use change.

The fuel output from available biomass supplies can be maximised by integrating biomass production pathways with renewable hydrogen. These integrated solutions offer opportunities for a more sustainable biofuel production. They are especially relevant in the Nordic region with its large biomass resources from forestry, the competitiveness of offshore wind electricity generation and the availability of water.

Liquid hydrogen and ammonia could be used as shipping fuels in future, but their use is currently still in the demonstration phase. Ammonia's advantages are ease of transport, storage and distribution thanks to its physical and chemical properties, as well as the established trade of ammonia the fertiliser industry. If ammonia or hydrogen are adopted at scale, it will be essential to ensure that they are produced from low-carbon pathways. Producing them from current pathways, based on fossil fuels, would be more detrimental for the climate than the continued use of heavy fuel oil (including very low sulphur fuel oil).

In the Nordic countries, both government and the private sector provide strong leadership in environmental questions. Nordic governments have understood that support for environmentally-friendly technology can stimulate employment in the maritime sector and in ensuring its competitiveness. Government-sponsored research is thus often accompanied by industry partnerships and cluster initiatives that provide a fertile environment for innovation. Many schemes bring together multiple actors and ensure a full project cycle from research via the demonstration phase to market introduction and investment finance for customers willing to apply the new solution. This last step has been important to ensure that prototypes find their way into real-life application.

The adoption of alternative fuels will require close cooperation throughout supply chains between shipowners, operators, ports, fuel producers and distributors as well as legislators. The Nordic region is well placed to build on experience of developing guidelines for battery electric ships and the use of liquefied natural gas (LNG) as a fuel for shipping. Norway has also shown significant leadership by introducing carbon taxes, currently applied to domestic shipping.

Nordic countries also provide considerable state aid to the maritime sector, but only part of this aid targets the environmental performance of the shipping sector. In some cases, maritime state aid is actually a fossil fuel subsidy: shipping benefits from large-scale tax exemptions for expenditure on fuel, similarly tonnage taxes – very generous tax schemes for shipping firms based on the tonnage of their ships rather than their profits – apply to the shipping activities of the fossil fuel industries, such as the offshore oil sector.

What we recommend

Increase the energy efficiency of new and existing ships

Norway, Denmark and further countries have proposed mandatory technical or design efficiency improvements for the existing fleet (labelled EEXI) and a mandatory operational goal-based measure with carbon intensity targets at the ship level. Adoption of both proposals – or a proposal combining both measures – by the International Maritime Organisation (IMO) seems possible. It would help to achieve the IMO's 2030 carbon intensity target to reduce shipping CO_2 emissions by at least 40% from 2008 levels. However, it would require both stringent engine power limitations in the EEXI-proposal, ambitious carbon intensity targets and sanctions if carbon intensity targets at ship level are not met.

Leverage public sector procurement to stimulate the electrification of short-distance shipping

The electrification of short sea shipping and provision of onshore power supply, in which the Nordic countries are a world leader, should be further stimulated. Electrification could be expanded to harbour ships, tugboats and icebreakers by using the public sector's buying power regarding maritime services. The Nordic countries could also use their clout in shipping electrification to help set clear, global definitions for power requirements for different applications and that standards for onshore power facilities and all components of shore-side electricity supply systems are finalised or updated. Policies to promote the electrification of ships should align with measures for sustainable battery supply chains under development in the automotive sector.

Introduce regulations on lifecycle emissions of maritime fuels

Stakeholders should support the adoption of a lifecycle (or well-to-wake) framework for assessing energy use and GHG emissions of shipping fuels. Promoting an IMO standard or approval procedure for lifecycle based carbon emission factors, including in the framework of the IMO Energy Efficiency Design Index (EEDI) regulation, is a near-term priority. This is particularly important for LNG, which reduces tailpipe GHG emissions but can have significant upstream GHG emissions. The introduction of lifecycle accounting for the GHG emissions of shipping fuels (in particular for biofuels) should be accompanied by the development of criteria and minimum requirements on other sustainability issues, in particular for land use.

Put in place carbon pricing for shipping and policies that can reduce the carbon content of shipping fuels

Initiatives in Nordic countries for carbon taxes, environmentally differentiated port pricing and electricity tax exemptions for shore power connections could serve as inspiration for other countries wishing to move towards zero-carbon shipping. Various financial incentive schemes in the Nordics still require alignment with a zero-carbon strategy. Maritime state aid should be linked more closely to environmental performance. Tax exemptions for ship fuel should be phased out. Greening maritime state aid would also imply that the fossil fuel sector's shipping activities, such as for the offshore oil sector, should not benefit from the tonnage tax. The NO_x Fund is a pricing mechanism that can help to reduce carbon emissions from shipping and could be developed into a CO_2 or GHG Fund for shipping.

Advance the discussion on market-based mechanisms at the International Maritime Organization

The Nordic countries could support a review that maps state-of-the-art carbon pricing (market-based mechanisms). It could focus on policy practices developed over the last decade and also include findings of the IMO expert group on market-based mechanisms of 2010. From this review, a concrete proposal could be developed, that could assess the effectiveness and feasibility of measures such as, for example, a carbon levy, an emissions trading scheme, a low-carbon fuel standard or a hybrid approach.

Launch pilot projects to gain experience with new fuels and accelerate the adoption of safety guidelines

The Nordics’ many pilot projects for new fuels make it a proving ground for the low-carbon shipping fuels of tomorrow. Norway in particular has played an important role in the development of international codes on the use, transport and storage of low-flashpoint fuels. .Research and additional pilot projects on promising fuels such as ammonia, liquid hydrogen and advanced biofuels, in a range of shipping segments, are important to address technical challenges associated with the use of new marine fuels. The results of current and planned pilots can accelerate their worldwide adoption, supporting the development of new or updated safety guidelines. The capacity, experience and leadership of Nordic stakeholders will be a precious resource, in this context.

Introduction

Decarbonising shipping remain a challenging task. By 2050, shipping tonne kilometres are projected to triple from 2015 levels (ITF, 2019a), and CO_2 emissions set to increase by 135% from 2018 levels (IEA, 2020a). Reducing its environmental burdens will require the deployment of technologies at an unprecedented rate, reinforced by effective international policy. Nordic countries are among those with the highest ambition and greatest number of maritime technology demonstrations in the world. The Danish shipping industry, for example, aims to be carbon neutral by 2050. Similarly, the Norwegian Shipowners' Association aims to halve emissions from 2008 levels by 2030, and be carbon neutral by 2050.

Transporting freight by sea remains the cheapest and most energy efficient method to move large volumes of goods around the world, due to the size of modern vessels. Every year, the maritime sector delivers approximately 80% global trade volume of physical goods (UNCTAD, 2019). Despite the efficiency of maritime transport, the sheer scale of the global shipping industry means that the sector was responsible for an energy consumption of 9.1 EJ in 2018 – mostly from heavy fuel oil (HFO) and marine diesel – leading to 1 076 million tonne (Mt) of GHG emissions (expressed in CO_2e) (IMO, 2020a). This corresponds to 3% of global energy-related CO_2 emissions, making the shipping sector a large contributor to climate change. In addition, the combustion of current marine fuels, especially HFO, produces large quantities of air pollutants, which have adverse health effects on populations living near ports (Merk, 2014). In 2018 the international shipping sector was estimated to have produced 11.4 Mt of SO_x, 1.73 Mt of PM_{10} and 1.59 Mt of $PM_{2.5}$ under the vessel-based allocation (IMO, 2020a).

The challenges are significant, but international action is underway. The International Maritime Organisation (IMO) is establishing an Initial Strategy on the reduction of GHG emissions from ships. It will development ambitious measures to be implemented for effective change and can build upon recent successes in addressing emissions of other pollutants: the IMO reduced the sulphur content of maritime fuels in 2020, and action has also begun to reduce NO_X emissions.

Europe, more broadly, is determined to achieve sizable emission reductions, with ambitious policies on GHG emission abatement. The European Commission aims to make Europe the first climate-neutral continent by 2050, to keep climate change in check (EC, 2019). This commitment is underpinned by the European Union's new growth strategy, the European Green Deal, which aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy. Reducing transport emissions will remain one of the key pillars needed to fulfil this ambition.

The Nordic countries of Denmark, Finland, Iceland, Norway and Sweden are at the forefront of this objective. Norway has pledged to reduce its greenhouse gas emissions by at least 40% from 1990 levels by 2030 and at least 80% by 2050 (Government of Norway, 2018). Denmark is committed to reducing GHGs by 70% from 1990 levels by 2030 (Danish Ministry of Climate Energy and Utilities, 2019). Finland aims to be net zero by 2035 (Finnish Ministry of the Environment, 2020a), Iceland by 2040 (Icelandic Ministry for the Environment and Natural Resources, 2018) and Sweden by 2045 (Swedish Environmental Protection Agency, 2019). Nordic countries produce some of the lowest carbon electricity in the world and are leaders in the uptake of low-carbon technologies such as electric vehicles (IEA, 2018) and energy efficient buildings.

European and Nordic leadership in sustainability issues is also visible in the shipping sector. The European Parliament has recently approved the inclusion of CO_2 emissions from the maritime sector in the EU Emissions Trading System (ETS) using revenues to support investment in innovative technologies and infrastructure aiming to decarbonise the maritime transport sector. Further developments will follow negotiations with member states on the final shape of the legislation (European Parliament, 2020).

Meeting these ambitious goals is likely to require significant research and development. Maersk, the Danish and largest container shipping company in the world, has recently set up a research centre to further decarbonisation of the shipping industry and achieve a carbon-neutral fleet by 2050 (Maersk, 2020). Research efforts are not restricted to incumbent stakeholders in the Nordic region. Encouragingly, R&D projects to help facilitate the decarbonisation of shipping are also being carried out by companies not traditionally associated with the maritime industry, such as power distribution networks, ammonia production facilities and forestry companies.

The quest to lower maritime emissions in the Nordic region is also giving birth to a number of new companies observing opportunities in new markets. Finnish company Norsepower, which specialises in rotor sails is one and Swedish company Echandia, a maritime battery manufacturer, another. The movement towards battery-operated ferries has prompted three of the biggest marine battery manufacturers to install factories in Norway. The burgeoning ecosystem of Nordic companies should beckon other countries to move forward. The advantage of pioneering this movement means the Nordic region is well placed to develop the international regulation on future fuels and technologies that may then serve as a template for the global maritime industry.

This report analyses future energy-use in the shipping sector of the Nordic region. In particular, the report assesses a range of technical and regulatory solutions that could allow the Nordic shipping sector to meet energy and environmental policy goals, including energy diversification, the reduction of local pollutants and GHG emissions savings.

- Chapter one of this report reviews the energy efficiency and fuel technology options to achieve these goals and the status of their adoption in the Nordic region, with details of relevant demonstration projects.
- Chapter two then compares the relative merits of some of these fuel technologies and their potential to decarbonise the global shipping sector.
- Policy will continue to play a key role in stimulating the deployment of technologies in the maritime transport sector. Chapter three of this report reviews government policies developed in the Nordic maritime sector. It provides an overview of visions and policy goals in each Nordic country, a review of the research and innovation policies that are in place and an assessment of pricing and incentive policies relevant for the decarbonisation of maritime transport.
- Chapter four brings insights from the technological analysis of Chapters one and two together with the policy assessments in Chapter 3. It identifies priorities for Nordic policy makers and stakeholders aiming to ensure a swift adoption of technologies in the Nordic region and contribute to a successful transition towards cleaner maritime shipping in the Nordic region. Given the global leadership of Nordic countries on decarbonisation, this can helps ensure that the Nordic experience can be inspirational and groundbreaking for the global transition.

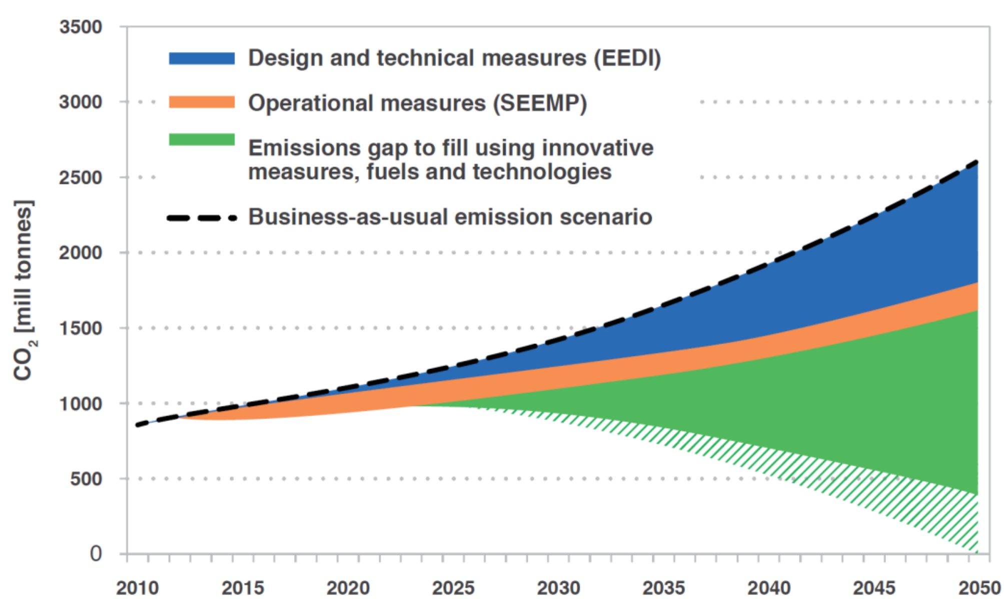
Technologies to decarbonise maritime transport

Reducing greenhouse gas (GHG) emissions and air pollutants from the maritime sector will require the widespread adoption of technological solutions. This chapter contains a summary of the main technologies and measures with the potential to lower the environmental impact of the shipping sector and includes an overview of the status of their adoption in the Nordic region.

The International Maritime Organisation (IMO) envisages the deployment of multiple technologies to reach GHG emissions reduction targets (Figure 1). These include energy efficiency improvements, operational measures and alternatives to existing petroleum-based fuels.

The first section of this chapter reviews measures to improve the technical and operational energy efficiency of ships. These measures are set to play an important role in cutting energy use in the maritime sector and thereby reduce GHG emissions and air pollutants. Energy efficiency can sharpen the economic competitiveness of the shipping sector by offsetting any additional costs from CO_2 pricing mechanisms, which are likely to be required to shift towards low-carbon fuels.

Figure 1. Pathway to achieve the International Maritime Organization's ambitious greenhouse gas reduction goals



Source: (IMO, 2020d).

The second section of this chapter focuses on fuel options available. This is important because better energy efficiency and operational improvements alone cannot keep up with the pace of decarbonisation needed to meet the GHG emissions reduction goals that were outlined by the IMO (Figure 1).

Increased energy efficiency in new and existing ships

Ships have lifetimes of approximately 25 years, meaning the turnover of the shipping fleet is slow. Approximately 80% of the 56 000 cargo carrying vessels in service globally today are likely to still be in service in 2030 (Pålsson, 2020). A range of technologies can improve the energy efficiency of these existing and new ships and reduce their reliance on fossil fuels. The most relevant are summarised in Table 2 (excluding electrification). Energy efficiency measures can be grouped into two categories:

- technical measures that save energy through design improvements
- operational measures that reduce energy use by altering the way ships are used.

Two policy instruments that address these measures are the IMO's Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). The EEDI aims to stimulate technical efficiency measures by establishing energy efficiency requirements of individual vessels, and is the first industry-wide global regulation of CO_2 emissions from ships (see Box 1). The SEEMP, also discussed in Box 1, aims to improve vessel operational efficiency.

Box 1. International Maritime Organization actions to improve the energy efficiency of ships

The IMO Marine Environment Protection Committee (MEPC) approved a series of amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI in 2011 to regulate the energy efficiency of ships (IMO, 2011). The two main measures introduced are the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP).

The EEDI began in 2013 and applies to all ships over 400 gross tonnes, which account for approximately 85% of global maritime GHG emissions. It requires that new ships meet minimum energy efficiency levels, based on the ship type and size segment. These levels are measured as a CO_2 intensity in grams of CO_2 per capacity mile (gross tonne-mile or deadweight tonne-mile[1]) and are reduced incrementally every five years. The aim is to stimulate the adoption of energy efficient technologies and practices. The first phase of EEDI, covering 2015 to 2020, required a reduction of CO_2 intensity of 10% with respect to the 2000-10 average. Later phases between 2020-25 and 2025-30 require carbon intensity reductions of 20% and 30% respectively. In 2019, the IMO also agreed to bring forward the entry into effect date of phase 3 from 2025 to 2022 for several ship types and to tighten the EEDI reduction for some ship types (e.g. 50% for containerships of 200 000 deadweight tonnage and above).

SEEMP measures, also adopted in 2011, apply to both new and existing ships and aim to improve energy efficiencies via operational measures such as optimising routes and speeds. In addition, from 2019, ships of 5 000 gross tonnes and above are also mandated to collect and transmit data related to their fuel oil consumption as part of the IMO's "data collection system for fuel oil consumption of ships" adopted in 2016 (IMO, 2016a).

The Initial IMO Strategy on reduction of GHGs from ships adopted by the 72nd IMO MEPC aims to phase shipping's GHG emissions out as soon as possible within this century. It sets out the following ambition to reach this vision:

- reducing CO_2 intensities of international shipping by at least 40% by 2030 and 70% by 2050 compared to 2008 levels
- peaking GHG emissions from international shipping as soon as possible

- "reduc[ing] the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them [...] as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals" (IMO, 2018).

Recent proposals from a group of IMO Member States including Finland and Norway include introducing an energy efficiency existing ship index (EEXI) to complement the EEDI (IMO, 2020b).

Table 2 includes estimates of the fuel saving potential of different energy efficiency solutions; these are expressed as a percentage reduction in energy use with respect to a benchmark where the solution is not integrated. These potentials are expressed as a range of values, due to the fact that energy efficiency improvements have different characteristics across different ship types and mission profiles. Some of the key determinants of this include: ship speed, ship and engine size, engine load profiles and the size of auxiliary power requirements (larger, for example in ships transporting goods that need to be maintained at specific temperatures and/or pressures than in ships transporting goods that do not have these types of requirements).

Despite this variability, the ranges included in Table 2 indicate the overall energy and GHG emission saving potential is significant. The overall efficiency improvement is close to 30% for retrofits and 40% for new designs. These are found by taking mid-point estimates, excluding slow steaming and size increases, and accounting for diminishing returns once multiple options are applied. Many of these improvements (starting from operational measures) also have a favourable cost profile with a capacity to be paid back by fuel savings[2] (ABS, 2014). Including slow steaming and size increases to ships pushes potential efficiency improvements to almost 60% (per tkm of cargo capacity) for new builds.

Wind assisting devices, such as Flettner rotors and aerofoils, are technologies seeing renewed interest to help reduce ship fuel consumption. Flettner rotors are large rotating cylinders which can harness the propulsive energy from wind by creating a pressure difference on either side of the cylinder. The magnitude of this force is dependent upon the wind's speed and direction. Flettner rotors have recently been installed on four ships by the Finnish company Norsepower (see Table 1). These include the cargo ship M/V Estraden, which operates between the United Kingdom and Belgium, the Viking Grace a cruise ferry sailing between Finland and Sweden, the Scandlines M/V Copenhagen, a RoRo ship operating between Germany and Denmark and, most recently, the tanker Maersk Pelican. The Maersk Pelican underwent 12 months of sea-trials beginning in September 2018 and reported an average 8.2% fuel efficiency improvement compared to the performance of the ship prior to the installation of its two rotors (Lloyds Register, 2019).

Table 1. Selected Flettner rotor wind propulsion demonstrators in the Nordic region

Ship name	Project partners	Status
Pelican	Maersk (Denmark), Norsepower (Finland), Lloyds List, Shell	Completed 2018, two rotors
M/V Estraden	Bore (Finland), Norsepower (Finland),	Completed 2014/15, two rotors
M/S Viking Grace	Viking Line (Finland), Norsepower (Finland),	Completed 2018, one rotor
M/V Copenhagen	Norsepower (Finland), Scandlines (Denmark)	Completed 2020, one rotor

Other wind-assisting devices include aerofoils, which are fitted to ships to harness wind power and reduce propulsion needs. Wallenius Marine a Swedish shipping company aims to produce a concept vessel by

2021. Dutch companies Boomsma Shipping and eConowind similarly aim to trial aerofoils on ships between 2020 and 2021 (VPO, 2020).

Table 2. Technologies enhancing energy efficiency and diversification on ships

Energy efficiency solution		Energy and GHG emission savings
Design and technology options		
Design modifications and structural optimisation	Increase in ship carrying capacity	10% (for larger ships) to 25% (for smaller ships)
	Increasing the length/beam ratio	3% to 5%
	Higher strength steel, material substitution	0% to 1%
Reduction of drag/skin friction	Hull surface texturing	2.5% to 7.5%
	Air lubrication	0% to 13%
	Wake equalising and flow separation reduction	1% to 3%
Increasing propulsion efficiency	Pre-swirl devices	2% to 6%
	Post-swirl devices	2% to 6%
	High-efficiency propellers	3% to 10%
Renewable energy integration	Sails	Up to 30% in best cases, where applicable
	Flettner rotors	8% on average, and up to 20% in best case, broader applicability than sails
	Solar electricity	0% to 1%
Machinery improvements (main and auxiliary engines)	Main engine performance measurement and control	1% to 2%
	Waste heat recovery	5% to 11% (requires large engine power)
	Engine hybridisation and optimisation of engine size, power and loads (includes de-rating)	0% (steady engine load) to 24% (dynamic load)
Operational improvements		
Speed reduction		27% hourly fuel consumption reduction at 10% reduction in speed
Weather routing		2% to 5%
Trim/draft optimisation		1% to 2%
Hull and propeller condition management and maintenance		3% to 12%
Ship system management – Includes reducing on-board energy use, fuel consumption measurement and reporting		Enabler of energy saving technology developments
Overall energy efficiency management – Includes the application of the IMO Ship Energy Efficiency Management Plan (SEEMP)		Enabler of energy saving technology developments

Source: ITF elaboration based on (ABS, 2014; ISO, 2017; Comer et al., 2019; Si, 2019; Chua et al., 2020; DTN, 2020; GSF, 2020; Rutherford et al., 2020; Smith, 2020)

Energy efficiency solutions can be cost-effective, as confirmed by a recent project undertaken by the Denmark organisation, Green Ship of the Future. They demonstrated the financial viability and significant emissions saving potential of retrofitting existing ships with energy efficient technologies. In 2019, real-world data determined the likely efficiency improvements from a range of energy efficiency technologies installed on two tankers owned by Hafnia and Maersk and a Ro-Pax ferry owned by DFDS, a Danish shipping company. The engineering estimates resulted in savings of between 11% and 27% with payback periods of less than three years, with additional savings possible if longer payback periods were to be considered (GSF, 2020).

Reducing hull fouling in particular can provide large efficiency improvements with short payback periods, the efficiency improvements from Flettner rotors on the other hand, have a payback period between six to ten years (GSF, 2020). In the Nordic region, Maersk reported a 41% reduction in CO_2 emissions between 2008-18 (Maersk, 2019b) through a range of technical and operational improvements including larger vessel capacity and improved propellers and bulbous bows. However, the adoption of energy efficiency shipping technologies is often limited due to a number of market barriers, including capital availability constraints, split incentives[3] and unreliable information on fuel use (Stulgis et al., 2014; Fitzpatrick et al., 2019).

The energy efficiency measure with the lowest technological barriers to adoption is slow steaming. The fuel consumption of a ship increases quadratically as the speed increases (e.g. it quadruples if the speed doubles). Slow steaming refers to the process of reducing ship speeds to manage excessive energy use, and could be implemented on both new and existing ships.

Slow steaming is not without complexity, due to the need to reorganise shipments and routes to ensure high capacity utilisations, and higher overall capacity requirements (Jivén et al., 2020). However, it has already been widely practiced by many global shipping companies since the 2008 financial crisis – and the relatively high fuel prices and shipping overcapacity that followed – with shipping speeds dropping by 20-30% between 2008 and 2015 and stabilising since (Rutherford *et al.*, 2020). In the Nordic region, Maersk reported a 41% reduction in CO_2 emissions between 2008 and 2018 (Maersk, 2019b). This estimate includes improvements from several solutions, including slow steaming. Increases in vessel size also played a large part in this reduction.

The current benefits of slow steaming can be locked-in to avoid a rebound in ship speeds again by using engine power limiting devices or engine de-rating. This is (also relevant in light of Covid-19 induced reductions of economic growth, and therefore maritime transport demand, since slow streaming comes with an overall reduction in the flows of goods that can be moved at any point in time). The majority of large ships operate their engines at around 50% of the maximum engine rating. This means that any policies seeking to limit engine power and lower ship speeds further would need to be aggressive and limit engine power by over 30% to have an appreciable effect on ship emissions (Rutherford *et al.*, 2020). Safety concerns must also be addressed in the balance.

In summary, several technologies for energy efficiency improvements in ships are already available. This is important to note as several novel ship fuels require further time for research and development. Energy efficiency measures with even modest annual savings (Table 1) can lead to significant cumulative emissions savings in the coming decades. R&D and demonstration funding can quicken development and uptake of technologies under trial in the global shipping fleet.

Technical improvements to new ships alone will not meet carbon targets in line with the Paris climate goals. Therefore, it will be important to ensure that fuel-saving technologies are also deployed on existing ships (through retrofits), beginning -in the early 2020s (Bullock *et al.*, 2020). Slow steaming is also important, especially considering that economic downturns will induce oversupply in maritime transport services.

Alternative fuels

Reductions in the GHG intensity of fuels used in the maritime sector must complement energy efficiency solutions to meet climate targets. This section dissects the main alternatives to the petroleum-based liquid fuels that currently account for the majority of shipping energy supply. It reviews fuels (energy vectors) that have the greatest market relevance today because of their cost competitiveness and other fuel options that have a greater decarbonising potential.

The energy vectors reviewed here include liquefied natural gas (LNG), methanol, biofuels, hydrogen, carbon-based synthetic fuels, ammonia and electricity, along with shore power and cold ironing. The main characteristics and production methods for each energy vector are explained, as well as their deployment status in the Nordic region.

Liquefied natural gas

Interest in liquefied natural gas (LNG) as a shipping fuel has grown recently, primarily in response to global policy limits on sulphur and NO_X levels found in currently-dominant shipping fuels. LNG is currently obtained from fossil methane. It is cooled to -162°C to increase its energy density (i.e. energy per unit volume) to reduce on-board storage volume, which enable its long-distance transport for trade purposes or its use as shipping fuel. Additional reasons for the uptake of LNG as a shipping fuel stem from its competitive cost, compared with other petroleum-based low-sulphur fuels. This is due to the decoupling of oil and natural gas prices that followed the growth in gas production in the United States and the increase in LNG trade volumes.

In 2015, the sulphur content of fuel for ships operating in designated Environmental Control Areas (ECAs) was limited to 0.1% by mass. In 2016, the IMO's Marine Environment Protection Committee (MEPC) confirmed the decision to limit the sulphur content of shipping fuels globally, reducing it from 3.5% to 0.5% by mass beginning in 2020 (IMO, 2020f).

These changes to policy include the development of technical regulations and standards that are specifically applicable to LNG ships, focusing on all LNG-fuelled ships, and not exclusively on LNG carriers. The IMO and the International Organization for Standardization (ISO) led this work, with contributions from classification societies and industry groups and significant leadership from the Nordic countries, in particular the Norwegian Maritime Authority. Important international regulatory texts, all finalised in the past five years, are listed in Table 3.

The use of new fuels in ships requires comprehensive safety arrangements concerning use, transportation and storage aspects. The "International Code of Safety for Ships using Gases or other low Flashpoint Fuels" (IGF Code) is one regulation that addresses fuels such as LNG, with a low flashpoint (the temperature of ignition). The use of any new type of fuel would require amendments to the IGF Code, to cover the unique characteristics in the handling and use of each fuel.

Table 3. International technical regulations and standards for liquid natural gas ships

Regulation or standard	Organisation	Subject covered	Year of application	Applies to
Guidelines for systems and installations for supply of LNG as fuel to ships ISO/TS 18683	International Organization for Standardization (ISO)	Minimum requirements for the design and operation of LNG bunkering facilities, including the interface between the LNG supply facilities and receiving ship. Applicable to bunkering of both seagoing and inland trading vessels. Covers LNG bunkering from shore or ship LNG supply facilities. Includes requirements and recommendations for operator and crew training, roles and responsibilities of ship crew and bunkering personnel during bunkering, and functional requirements for safe bunkering.	2015	LNG-fuelled ships
International Code of Safety for Ships using Gases or other low Flashpoint Fuels IGF Code	International Maritime Organisation (IMO)	Safety-related requirements for the arrangement and installation of machinery, equipment and systems for LNG-fuelled vessels.	2017	LNG-fuelled ships

Sources: IMO (2014, 2017, 2020e, 2020c); ISO (2015).

The successes that Nordic countries have had with LNG are largely enabled by abundant gas supplies, especially in Norway. Additionally, they have had:

- Government support with incentives provided by the Norwegian government to develop the industry for LNG as a maritime fuel. This includes a tax on nitrogen oxide emissions in 2007 and the Business Sector NO_X Fund in 2008, which diverted some of the NO_X taxes toward subsidising LNG-fuelled ships (see Chapter 3).
- Supranational action, for example, the Alternative Fuels Infrastructure Directive (2014/94/EU), requires European member states to take part in the construction of a core network (the Trans-European Transport Network) of both marine and inland ports with LNG bunkering and in the case of the development of standards for LNG refuelling.
- Local shipping routes with predictable journey patterns (e.g. roll-on/roll-off ships, cruise ships and ferries).
- Stricter and earlier environmental requirements set in the Baltic Sea and North Sea ECAs, established in 2005 and 2006 due to the susceptibility of the regions to acidification.
- A longer history of LNG use to rely on and refer to. This includes pioneering the development of the technical regulations and standards related with fuel and refuelling safety, as well as ship safety and construction requirements.

Despite the advantages in terms of fuel cost and low sulphur content, LNG is currently the least common option chosen to comply with sulphur regulations (Jaffe, 2019). Ships equipped with scrubbers that strip SO_X from exhaust gases out favoured LNG-fuelled ships in 2019. And very low sulphur fuel oil (VLSFO) is by far the most common shipping fuel in early 2020 after largely replacing heavy fuel oil (IEA, 2020b; Kulsen and Loozen, 2020).

The limited adoption of LNG is largely due to the in-depth modifications required to switch existing ships from heavy fuel oil (HFO) to LNG. In comparison, scrubbers on ships are easier to retrofit and switching to VLSFO does not require modifications. The relative challenges of converting existing ships to use LNG, means that the uptake of LNG as a shipping fuel has been mainly driven by new ship orders, inevitably resulting in a progressive phase-in. Other barriers include lower flexibility in terms of port calls beyond the Nordic region, as this requires a wide availability of bunkering infrastructure.

LNG also has the potential to reduce emissions of sulphur oxides and other local air pollutants (in particular NO_X and particulate matter) in addition to the benefit of energy diversification from petroleum-based fuels. The use of LNG leads to approximately 20% fewer direct CO_2 emissions compared with petroleum-based fuels, thanks to the comparatively low-carbon content of methane (IMO, 2016b).

However, the use of LNG in ship engines often leads to methane slip. This is a phenomenon whereby a fraction of natural gas passes through the engine unburnt and releases into the atmosphere. Since methane is a powerful GHG, this greatly reduces the climate benefits of using LNG as a shipping fuel. The severity of methane slip in highly dependent upon the engine design used, with high pressure engines leading to fewer methane emissions than low pressure models (Pavlenko et al., 2020). Additional issues that further reduce the benefits of LNG as a shipping fuel relate to recent evidence that upstream methane leakage could be higher than previously expected (Schwietzke et al., 2016; Alvarez et al., 2018; Hmiel et al., 2020). Together, these factors mean that the life-cycle and well-to-wake GHG emissions of LNG are in many cases worse than conventional maritime fuels[4]. These considerations indicate that LNG faces challenges to mitigate GHG emissions in maritime transport. Enabling better performances requires a switch to technologies that minimize methane emissions in both engines and the fuel supply chain.

Liquid natural gas demonstration projects in the Nordic region

Demonstration projects identify technical challenges and develop safety requirements for new fuels. Guidelines on the use of fuels and amendments to the IGF Code can only be made with knowledge developed over a series of tests and demonstrations. It is possible to produce ships that run on fuels that are not yet covered by the IGF Code through an alternative design category. It is more difficult and costly to approve ships in this way but is necessary for new demonstration projects.

During the early 2000s, the Norwegian Maritime Authority (DNV GL) and other stakeholders began to develop the rules and regulations for the use of LNG as a ship fuel in Norway. In 2004, DNV GL submitted an initial proposal to the IMO Maritime Safety Committee, and interim voluntary guidelines were adopted in 2009 (IMO, 2009). The IGF Code was eventually adopted in June 2015 and confirmed on 1 January 2017 (IMO, 2017). Compliance became mandatory through amendments to the IMO's International Convention for the Safety of Life at Sea (SOLAS), concerning the safety of merchant ships, which lengthened the time for completion and approval

As of 2019, there were 539 LNG carriers fuelled with LNG and an additional 217 other LNG-fuelled ships in operation globally, consisting mostly of passenger ferries, cruise ships, offshore supply ships, oil and chemical tankers (Pavlenko *et al.*, 2020). The majority of LNG-fuelled ships burn the fuel in an internal combustion engine. However, demonstration projects in the Nordic region have also used alternative powertrains such as the Viking Lady, a ship equipped with a high temperature 320 kW molten carbonate fuel cell using LNG in 2009 (DNV-GL, 2015).

Over half of the world's non-carrier LNG-fueled ships operate in the North Sea and Baltic Sea. The Nordic region has the most- developed LNG bunkering infrastructure globally (Jaffe, 2019). As of January 2019, there were 22 ports with LNG bunkering capacity in the Baltic Sea Emissions Control Area (ECA), 18 such ports in the North Sea ECA, and a further 49 such ports in the rest of the European Union, mostly coastal. Another 50 LNG bunkering ports were in development as of April 2019 (Jaffe, 2019).

Methanol

Methanol, a widely-traded commodity, is another fuel proposed to help decarbonise the shipping industry. It is a liquid fuel at ambient temperature, can be used with existing ship engines and bunkering infrastructure with relatively minor modifications and it is easier to handle than gaseous fuels such as LNG. It is miscible in water and less hazardous to the environment than diesel or heavy fuel oil, biodegrading rapidly in the event of a spill (DNV GL, 2020a). When combusted, methanol produces fewer air pollutants compared to HFO, with 99% less SO_X, 60% less NO_X and 95% less particle matter (PM) (Balcombe et al., 2017). Methanol is available through existing infrastructure in more than 100 ports globally (DNV GL, 2020a). These characteristics made it a potential candidate to meet the policy requirements set for the Baltic Sea and North Sea ECAs on local pollution, leading to a number of demonstration projects.

Nevertheless, the majority of current methanol production is derived from natural gas and coal. This means that that the life-cycle process of this fuel leads to significantly worse GHG intensity than HFO under current conditions (Balcombe *et al.*, 2017). Emissions occurring in the fuel production phase can theoretically be reduced with carbon capture, use and storage technologies. However, the combustion of methanol in ship engines will always produce CO_2, meaning that carbon capture and storage (CCS) technologies alone will not be sufficient to deliver large well-to-wake GHG emission reductions for methanol fuel produced using fossil fuels. An alternative is to produce methanol using biomass and waste to significantly improve its GHG emission intensity. Methanol produced in this way is considered a biofuel and is discussed in the following section. Methanol could also theoretically be produced from hydrogen and waste CO_2, this is discussed in the broader framework of synthetic fuels.

Methanol demonstration projects in the Nordic region

Today, there are eleven ships that use methanol as a fuel with a further nine currently under construction (Wingrove, 2020). They include a number of chemical (methanol) carriers flying the Norwegian flag. Sweden has taken an active role in the development of methanol-powered ships. A pilot project was launched in 2015 to convert the Stena Germanica, a large passenger and car ferry operating between Gothenburg (Sweden) and Kiel (Germany), to use methanol fuel for the first time. The Finnish engine manufacturer Wärtsilä was involved in the engine retrofitting (ITF, 2018a).

Methanol was also tested in 2010 in a Solid Oxide Fuel Cell (SOFC) as part of the EU-funded Methanol Auxiliary Power Unit (METHAPU) project, which included Nordic companies such as Wärtsilä, Wallenius Marine and Det Norske Veritas. As part of the project, a 20 kW fuel cell was used to provide auxiliary power on the M/V Undine, a RoRo passenger vehicle ship (CORDIS, 2008).

Biofuels

Biofuels are gaseous or liquid fuels relying on biomass as their main feedstock. Gaseous biofuels, also known as biogas, are primarily produced from the anaerobic digestion of biomass and waste from agriculture and livestock and are largely used for electricity and heat generation (IEA, 2019a). Biogas can be upgraded to biomethane and substitute fossil based transport fuels. If produced from waste and liquefied, it can be blended with LNG, reducing its well-to-wheel carbon content.

Liquid biofuels, have the advantage of requiring relatively minor adjustments to the fuel distribution infrastructure already in place. This is especially true for those capable of being blended directly in their petroleum-based homologues, known as drop-in biofuels, and can have important advantages in terms of cost reductions. Currently, liquid biofuels consist primarily of ethanol produced from plant-based sugars, starches and other biomass and biodiesel primarily derived from vegetable oils, such as from palm, soybean, and rapeseed, either in their virgin or recycled form (animal fats and other waste oils may also complement these). Taken together, these forms of liquid biofuels accounted for 91% of global biofuel production in 2018 (IEA, 2019a). However, only a negligible fraction of these fuels is currently used in maritime transport.

Drop-in and blend-in biofuels for maritime applications

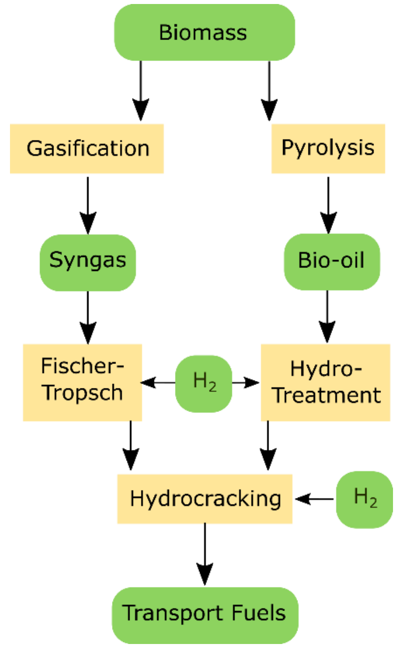
Drop-in and blend-in biofuels can be fully or partially blended with petroleum-based shipping fuels using existing fuel distribution infrastructure. They have the best properties to be combusted in shipping engines. They may be issued from the biochemical, oleochemical/lipid and thermochemical production pathways. The following sections review these options, given their relevance for future developments of low-carbon shipping fuels.

Biofuel production through *biochemical* conversion processes occurs primarily through the fermentation of sugars (either directly using sugar cane or from starches using corn) to short chain alcohols (ethanol in particular) for conventional biofuel production (first generation biofuels). Advanced processes, namely enzymatic hydrolysis, expanded the scope of short chain alcohol production to cellulosic biomass as primary feedstock. Maritime transport largely makes use of heavy fuels or, similar to aviation, middle distillates. For biochemical pathways to play a role in shipping, the products of biochemical fuel processes need to be reshaped to longer hydrocarbon molecules (IEA Bioenergy, 2019). For aviation fuels, production costs for biochemical pathways are estimated to be higher than for oleochemical pathways (ICAO, 2018). Even if these fuels can be technically suitable for ships, less strict requirements on shipping fuel quality indicate that cost challenges are greater than in aviation. This suggests that shipping applications of *biochemical* biofuels may only be viable as an off taker of the remaining fractions of biochemical processes primarily aiming at aviation or other markets where bio-based materials have higher economic value.[5]

The *oleochemical/lipid* biofuel production pathway focuses on the conversion of lipid feedstocks (e.g. vegetable oils, animal fat or used cooking oil) through hydrogenation into high-quality paraffinic fuels, including hydrotreated vegetable oil (HVO) in particular, that are fully compatible for drop-in blending with petroleum-based fuel in the diesel pool (IEA Bioenergy, 2019). This process is pioneered, in the Nordic region, by Neste, Finland. Earlier technologies converting oleochemical/lipid feedstocks into transport fuels consisted in the trans-esterification of vegetable oils or animal fats into Fatty Acid Methyl Esters (FAME biodiesel). Low-carbon production of fuels from all the oleochemical/lipid pathways is limited by the low availability of waste oils/fats and subject to challenges for land use and land-use change for vegetable oils. Production costs largely depend on the cost of waste or biogenic oil feedstocks, which tend to be more expensive than crude oil. This means that oleochemical/lipid biofuels can compete with petroleum-based alternatives only with cost reductions (e.g. from streamlining supply chains waste oils) or in the presence of carbon taxes, even if some cost reductions are also possible from increases in production scales.

Thermochemical pathways largely consist in the conversion of ligno-cellulosic feedstocks to bio-based intermediates, followed by their conversion into fuels suitable for maritime transport. Feedstocks include: wood, energy crops, some forms of municipal solid waste and residues from agriculture and forestry. Three main families of conversions (two of which are included in Figure 2) characterise these thermochemical pathways: pyrolysis, hydro-thermal liquefaction and gasification. The end product is liquid (bio-oil/biocrude) for the first two and synthesis gases (syngas) for the third.

Figure 2. Biomass to transport fuel: Process routes for major thermochemical drop-in fuels



Note: This is a simplified representation of the conversion processes.

Source: Based on IEA Bioenergy (2019).

Bio-oil, a dark brown liquid with a similar physical appearance to crude oil, but chemically distinct, has a lower hydrogen/carbon (H/C) ratio and contains a significant fraction of oxygen. This fraction gives it an undesirably high reactivity (low chemical stability) and a lower energy density (less than 50%) than crude oil. Water is a major component of bio-oils and its concentration varies depending on the initial moisture content of the biomass and the production process. Bio-oils can be obtained from pyrolysis or hydrothermal liquefaction, as the result of the thermal decomposition of feedstock through exposure at temperatures ranging between 200-500°C, eventually combined with catalytic cracking, with the aim to reduce oxygen content.

While bio-oil production is relatively inexpensive, its quality must be upgraded to be suitable for use in transport applications. This increases cost significantly and entails several technological challenges. Hydro processing (including hydrotreating and hydrocracking) is a key step to increase the H/C ratio of bio-oil, making it suitable for the production of transport fuels. A noteworthy production challenge is the need for deoxygenation of the bio-oil, while maintaining high conversion yields and high hydrogen to carbon ratios in the finished fuel.

Due to the need for hydro processing, bio-oil upgrade can be integrated into existing refining processes, with potentially significant capital cost savings. Like the integration of renewable hydrogen in refining, this can also effectively reduce GHG emissions. The expansion to a range of bio-based intermediates (bio-oils/biocrudes) with a higher oxygen content, beyond the initial focus on lipids, is also an area of potential development of biomass feedstock integration in refining. This would widen the range of biomass feedstocks that refineries can use to produce fuels with a lower content of fossil carbon, but it is currently still at a low technology readiness level (IEA Bioenergy, 2019).[6]

The second family of thermochemical pathways for biofuel production involves biomass gasification. This is typically conducted at high temperature and pressure conditions to convert biomass to a mixture of hydrogen and carbon monoxide, known as synthesis gas or syngas. The syngas is then converted into different forms of liquid hydrocarbons via a process known as Fischer Tropsch (FT) synthesis.[7]

FT synthesis has commercial applications globally. The energy company SASOL produces synthetic hydrocarbons using coal as feedstock (coal-to-liquids) in South Africa. It also has large-scale gas-to-liquids plants that convert natural gas into liquid fuels in Malaysia, Nigeria, Qatar and South Africa (Nichols, 2017). FT-based fuel production from biomass has been used in demonstration plants in Europe and North America (ETIP Bioenergy, 2020a, 2020b). When biomass is the feedstock, this process is typically called biomass-to-liquids (BtL).

The BtL pathway requires the removal of impurities such as small char particles, tar vapors and volatile nitrogen and sulfur compounds, which occur after biomass gasification. This is otherwise known as syngas cleanup, and is technically challenging (IEA Bioenergy, 2019). BtL also faces difficulties to increase scale, due to the inherent limitations from the sparse nature of the biomass feedstock, and risks, due to limited experience. These technical issues have repercussions on costs, with the cost gap with petroleum-based fuels estimated to be higher than oleochemical pathways. Similarly to oleochemical pathways, additional challenges come from the lower fuel-quality requirement typically characterising shipping fuels, widening the biofuel cost-gap with petroleum-based alternatives.

BtL fuel production can be enhanced by integrating low-carbon hydrogen from renewable-energy electrolysis: a process known as Power and Biomass to Liquids (PBtL). This augments the H/C ratio and increases the energy yield of fuels from a given carbon content of biomass feedstocks (Hannula, 2016b). It produces synergies that reduce the electricity needed for hydrogen production per unit energy in the fuel[8]. PBtL fuels therefore have advantages to address sustainability challenges, among them: land-use requirements; an issue for the scale up of biomass demand, and, material/resource intensity; an issue for the scale up of renewable electricity.

Biofuels may reduce GHG emissions compared with existing fossil fuels. Production processes, from land use and biomass cultivation to the harvesting and final conversion into fuel, determine whether this is the case. Biofuel production may also have impacts on deforestation, loss of biodiversity and competition with local food supplies through competition for land with other uses. Depending on the characteristics of the land directly or indirectly displaced, land-use change effects may have additional implications on the GHG emission balance of biofuel production. For example, replacing carbon-rich peatlands or primary forests with biomass cultivation for biofuel production is likely to lead to net increases in GHG emissions, due to the loss of stored carbon in the land and other carbon sinks (Penman *et al.*, 2006).

In general, the biofuels offering the largest GHG emission abatement are those best integrated in biomass use and harvesting processes, with high yields per hectare, a low likelihood to compete directly (due to the need for the same feedstock, e.g. corn) or indirectly (e.g. due to the need for arable land) with food crops. They also require limited amounts of fossil fuels for their cultivation (e.g. in the form of fertilisers) and conversion (e.g. for heat generation) processes. The best performing biofuels in terms of GHG emission abatement and other sustainability aspects are generally those derived from organic waste, sludge, manures, woody/cellulosic biomass, algae and those that can combine sugar-, starch- or oil-bearing components with significant amounts of cellulosic biomass (e.g. sugar cane ethanol).

Demonstration projects in the Nordic region

The Nordic region has seen a number of demonstration projects on biofuel use in shipping. Second generation biofuels produced by Dutch company, GoodFuels were successfully tested on board the Nord Highlander owned by Danish shipping company Norden in 2018 (Pospiech, 2018). Similarly, in April 2020 Stena Bulk operated the Stena Immortal, a 183 m tanker, on 100% biofuel oil produced from used cooking oil by GoodFuels, for a ten-day journey across the Atlantic (Stenna Bulk, 2020). Liquefied biogas was trialled on a Norwegian ferry in 2016 and a Swedish tanker operated by Furetank in 2018 (Sjöström, 2018). In 2019, Maersk ran a large container ship between Rotterdam and Shanghai on a 20% biofuel blend made from used cooking oils (Maersk, 2019a). A small-scale application of HVO in shipping is the case of harbour bus shuttles in Copenhagen (Denmark) (Norberg, n.d.).

On the production side, UPM, a Finnish forestry company, operates a biorefinery in Lappeenranta and produces 130 000 tonnes of renewable diesel and naphtha by hydrotreating crude tall oil, a waste product from pulp production (UPM, 2020b). The company is reportedly testing the suitability of the fuel for maritime applications by collaborating on laboratory tests with Wärtsilä and Dutch companies Boskalis and GoodFuels (UPM, 2020a) and aims to scale up production to 500 000 tonnes in the near future (Fortuna, 2020).

Hydrogen

Hydrogen is an energy carrier of growing interest for maritime shipping. Once hydrogen has been produced to a high purity level, it can be used as a fuel in cells to produce electricity and provide mechanical traction through an electric motor. Hydrogen can also be used in an internal combustion engine, both pure and in a dual-fuel mixture with conventional diesel fuels.

However, hydrogen is not without disadvantages. Compressed hydrogen has relatively low energy density. To increase its energy storage density it must be liquefied, which incurs energy losses of approximately 30% and has significant impacts on costs. Liquid hydrogen must be stored cryogenically at -252°C and requires careful handling as it is explosive and permeates through materials making them brittle and prone to failure.

Pure hydrogen has low air pollutant emissions, with no sulphur oxide (SO_X) or particulate matter. Using hydrogen in combination with conventional diesel fuels in a dual-fuel engine can produce significant NO_X emissions and must be treated with selective catalytic reduction systems. When hydrogen is burned in an engine or used in a fuel cell it produces no carbon dioxide emissions, only NO_X emissions, as they depend on the temperature of combustion, and not the fuel. However, the production of hydrogen can release GHG emissions depending on the primary energy and production route used.

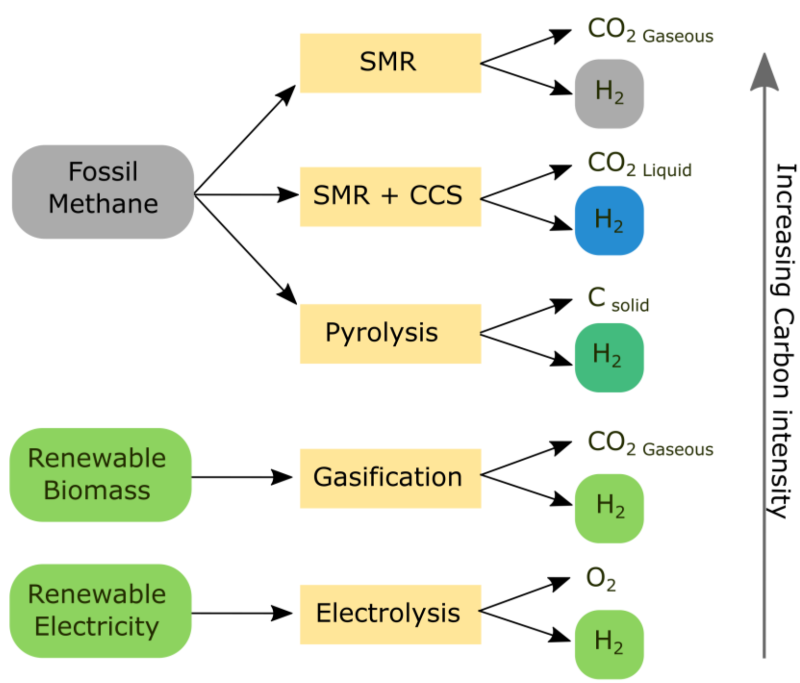
Fossil fuels are used to produce the majority of current global hydrogen demand, either by steam methane reformation (SMR) (76%) or coal reformation (23%) (IEA, 2019b). The production of hydrogen by reforming fossil fuels produces CO_2 process emissions. Three promising solutions to reduce emissions from hydrogen production include: *water electrolysis* using renewable electricity, applying *carbon capture and storage* technologies to existing fossil production methods or *methane pyrolysis*.

Producing hydrogen by *electrolysis* and using electricity from renewables has the potential to eliminate almost all hydrogen GHG production emissions. Hydrogen from electrolysis is already at a high level of technological maturity (TRL 8-9) (IEA, 2020c) but currently faces barriers due to higher costs than the main production methods in use.[9]

The carbon intensity of hydrogen produced by fossil fuel reformation could theoretically be reduced using *carbon capture and storage* (CCS) to sequester up to 90% of the process CO_2 emissions. However, unless upstream fugitive emissions associated with the extraction of fossil fuels are also addressed, applying CCS technologies to hydrogen production from fossil fuels would only reduce the lifecycle GHG emissions intensity by 60-70% (Parkinson et al., 2019; Royal Society, 2020).

Hydrogen production from *methane pyrolysis* involves anaerobically decomposing natural gas at high temperatures or in the presence of a catalyst, producing hydrogen and solid carbon. Because gaseous CO_2 is not produced in this process, hydrogen produced in this manner facilitates carbon storage. Methane pyrolysis is currently used to produce carbon black, a material used to reinforce vehicle tyres (Monolith Materials, 2020). However, as a method to produce hydrogen, it is currently at a relatively early level of technology readiness (TRL 6) (IEA, 2020c). Methane pyrolysis could theoretically reduce the GHG intensity of hydrogen by approximately 90% compared to existing steam methane reformation methods, provided low-carbon sources are used for heat and the transport of natural gas. This pathway will also remain susceptible to fugitive methane emissions in supply chains: unless they are effectively addressed, these reduce its climate benefits (Weger, Abánades and Butler, 2017; Parkinson *et al.*, 2019).

Figure 3. Selected hydrogen production pathways and their relative greenhouse gas emissions impact



Note: SMR = steam methane reforming; CCS = carbon capture and storage.

Demonstration projects

Early stage demonstration projects have been developed to address technical challenges of hydrogen as a shipping fuel. As part of the Zemships project, the first commercially used fuel cell passenger vessel, the Alsterwasser began operation in 2008 in Germany using two 48 kW fuel cells for propulsion (European Commission, 2020). Hydrogen fuel cells have generally been limited to small ships due to their relatively low power density compared with internal combustion engines. However, as the number of demonstration projects has grown, so too have the size of the vessels and fuel cells.

The European Union's Fuel Cells and Hydrogen (FCH) joint undertaking currently covers two hydrogen ship projects: FLAGSHIPS and MARANDA. The MARANDA project, which runs from 2017 to 2021, aims to use a 165 kW hydrogen proton-exchange membrane (PEM) fuel cell for auxiliary power on a research vessel. The 2019-22 FLAGSHIPS project covers two vessels: a utility vessel in France with 2x200 kW PEM fuel cells and a passenger car ferry in Norway with 3x200 kW PEM fuel cells for propulsion needs (Flagships, 2019). Norwegian companies Norled and Westcon aim to produce two hydrogen ferries by 2021 with capacity for 299 people and 80 cars each (Norled, 2019). In 2023, Norwegian shipowner Havila aims to install a 3.2 MW hydrogen fuel cell in a cruise ship, making it the largest hydrogen fuel cell fitted on a ship to date (Radowitz, 2020).

Synthetic hydrocarbons, including electrofuels

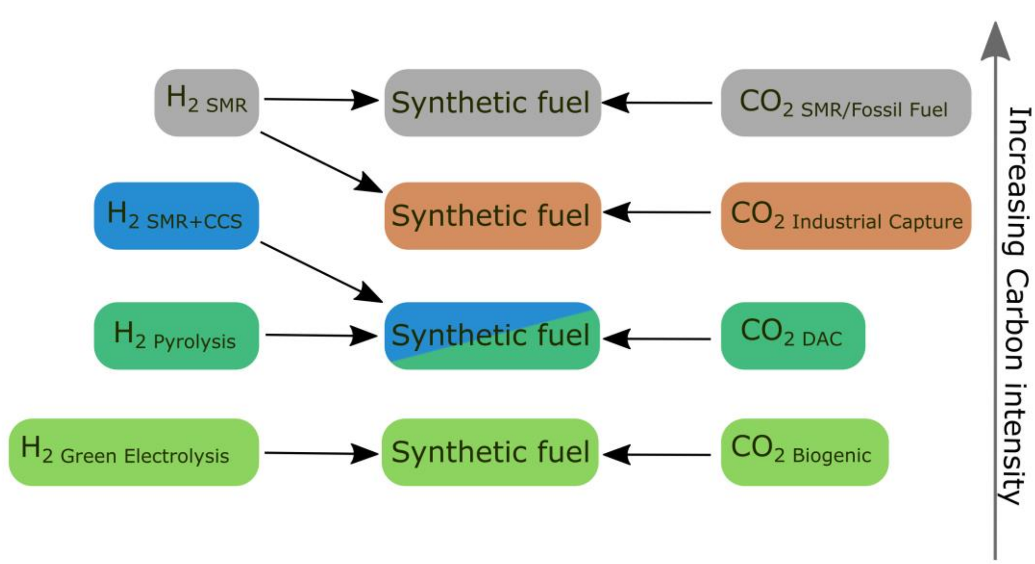
The combination of hydrogen with carbon building blocks can yield a range of different synthetic hydrocarbon fuels. These are gaseous (e.g. methane) or liquid states (e.g. methanol, gasoline and diesel). In cases where hydrogen is derived from the electrolysis of water, these synthetic hydrocarbons are classified as electrofuels. Like all synthetic fuels, electrofuels can be designed for direct blending with petroleum-based fuels or as a substitute, meaning there are relatively few technical barriers for their use in combustion engines for maritime transport.

The carbon intensity of synthetic hydrocarbons (including electrofuels) is dependent upon the net GHG emissions associated with the hydrogen and carbon-based reactants (Figure 4).

Low-carbon hydrogen production pathways, include electrolysis using renewable electricity, biomass gasification, methane pyrolysis and hydrogen produced with CCS. Carbon-based reactants with low GHG emissions intensities originate from biomass (such as biomass-to-liquid pathways, discussed in the biofuels section) but could also include direct air capture (DAC) of CO_2. DAC processes involve separating atmospheric CO_2 using amines and low temperature heat. Synthetic fuels produced using both low-carbon hydrogen and carbon inputs can have a low GHG emissions intensity, as the majority of the CO_2 produced during their use (e.g. in a ship engine) is offset by the carbon sink effect of the reactants (e.g. biomass). This closed-loop carbon cycle is essential if synthetic fuels are to lead to meaningful GHG emissions savings.

Alternative sources of carbon reactants include those sourced from industry or power generation by carbon capture of CO_2 emissions. Synthetic fuels produced using these feedstocks would be a net contributor to global GHG emissions when used in shipping, but may have a lower impact than the continued use of HFO.

Figure 4. Selected synthetic fuel production pathways and relative greenhouse gas emissions



Note: DAC = direct air capture.

The production of hydrocarbon electrofuels from biogenic carbon or DAC have the benefit to reduce pressure on land use, in comparison with BtL and other biofuel pathways. However, in the case of DAC, this comes at the cost of higher thermodynamic losses and it is therefore detrimental from the perspective of an efficient use of renewable electricity.

Cost estimates for liquid electrofuels from renewable electricity and DAC are approximately 3.1/L for liquid fuels (i.e. USD 300/MWh) (IEA, 2019b)[10], making them among the most expensive fuel production pathways. The rapidly decreasing cost of renewable electricity production (IRENA, 2020) is seen as an avenue to open up new opportunities for electrolysis and synthetic fuels, as electricity generation is the largest cost component of synthetic fuel production. With low electricity costs (USD 25/MWh), the costs of synthetic carbon based fuels may be reduced by a further USD 0.5/L (USD 50/MWh) (IEA, 2019b). Other costs reductions are possible if the cost of CO_2 (or biogenic carbon streams) are lower, but synthetic fuels using DAC are likely to remain comparatively expensive compared with other fuels.

Ammonia

Ammonia is increasingly considered as a low GHG marine fuel. Like hydrogen, it does not produce direct CO_2 emissions when burned in an engine. Furthermore, ammonia presents several advantages compared with pure hydrogen: it can be stored as a liquid by cooling to -33°C at ambient pressure or by pressurising to 10 bar at ambient temperature, it has a higher energy density than hydrogen, it is not explosive, and can use storage tanks similar to those used for liquefied petroleum gas (LPG). In addition, ammonia is already an internationally traded commodity with established handling procedures (Royal Society, 2020).

Burning pure ammonia in a compression ignition engine is challenging, requiring high compression ratios to ignite the fuel (Dimitriou and Javaid, 2020). To overcome this constraint, a pilot fuel with lower ignition temperature, such as diesel, is needed to facilitate combustion. Using conventional diesel for pilot fuel would limit the potential of fully achieving zero GHG emissions. However, this could be solved by using a pilot fuel with a low-carbon intensity such as hydrogen, biofuels or synthetic fuels. Hydrogen could possibly be created on board by cracking a share of ammonia fuel (Valera-Medina *et al.*, 2018). An alternative is to use ammonia in a spark ignition engine, though this is not as reliable as pilot-fuel ignition due to the flammability characteristics of ammonia.

The use of ammonia as a shipping fuel is currently at an early stage of technological maturity with several tests at laboratory scale (Valera-Medina *et al.*, 2018; Hansson, Fridell and Brynolf, 2020). Ammonia can be used in a fuel cell as an alternative to an internal combustion engine. If used in a solid oxide fuel cell (SOFC) then efficiencies in the order of 50-65% could theoretically be obtained (Giddey *et al.*, 2017), but the technology is less mature than ammonia used in ICEs. Finally, ammonia could be used in a gas or steam turbine, but would likely have lower thermal efficiency than an equivalent sized ICE.

The most common method to produce ammonia (NH_3) is the Haber-Bosch process, in which pure Nitrogen (N_2) obtained by air separation is combined with Hydrogen (H_2) in the presence of a catalyst. Currently, 72% of the global production of ammonia uses hydrogen produced from steam methane reforming of natural gas and 22% uses coal, mostly in China (Dimitriou and Javaid, 2020). There are currently two pilot plants testing power-to-ammonia concepts in Oxfordshire (United Kingdom) and Minnesota (United States) reporting production efficiencies of 50-60% (Dimitriou and Javaid, 2020). Ammonia can be produced by alternative means to the Haber-Bosch process using electrochemical reactions, but these methods remain in early research stages (Royal Society, 2020).

The carbon intensity of the hydrogen production pathway is crucial to determine the life-cycle GHG emissions of the ensuing ammonia production. Similarly, the energy intensity of ammonia productions depends largely on the hydrogen production pathway and the energy efficiency characteristics of the following conversion steps.

Ammonia produces nitrogen oxides (NO_X) and nitrous oxide (N_2O) emissions when burned. NO_X are local air pollutants and N_2O has high warming potentials (GWP_{100}=265) and could have detrimental effects to the environment if released into the atmosphere (IPCC, 2014). In theory, selective catalytic reactors can be used to remove these oxide emissions from exhaust gases, using ammonia in the process, but these technologies need to be demonstrated at industrial scale in marine environments and would need to be highly effective.

An additional challenge with ammonia is that it is a toxic chemical, caustic to both humans and marine life, meaning significant safety measures need to be adopted. Whilst many of these measures are already established to deal with current ammonia use as a fertiliser, additional safety considerations will be necessary to burn ammonia as a fuel, such as using double-walled pipes in engines to protect against leaks (MAN ES, 2019). There are already established guidelines for the transportation of ammonia as cargo on ships and ammonia is also used as an industrial refrigerant.

Demonstration projects in the Nordic region

Major ship engine manufacturers – including MAN ES and Wärtsila, both based in the Nordic region – have begun developing ammonia combustion engines. MAN ES, one of the main manufacturers of two-stroke engines for shipping applications, is currently developing an ammonia combustion engine and aims to produce engines capable of using ammonia by 2024, with tests scheduled to begin in 2021 (DNV GL, 2020b). MAN ES is not envisaging hydrogen as a shipping fuel due to technical challenges. Wärtsila, is working on both the development of ammonia internal combustion engines for use in shipping (typically four-stroke models for typical use in smaller ships than the two-stroke engines of MAN ES) and fuel cells. Unlike MAN ES, Wärtsila also plans to develop a hydrogen engine.

The Nordic region also has a large existing ammonia production capability. Norway's chemical company, Yara, is one of the largest producers of ammonia in Europe, turning out 530 000 tonnes per year (Yara, 2019a). Yara and electrolyser manufacturer Nel, are involved in a project supported by the Norwegian Research Council to produce ammonia via electrolysis and operate a 5 MW alkaline electrolyser by 2022 to supply the Porsgrunn site in Norway (1% of the production at the site) (Yara, 2019b). Haldor Topsoe, a Danish company that specialises in the production of heterogeneous catalysts and the design of process plants based on catalytic processes, recently announced a demonstration of an innovative ammonia synthesis plant. This uses a solid oxide electrolysis cell (SOEC) to make synthesis gas (hydrogen and nitrogen) feeding the Haber-Bosch process. According to Haldor Topsoe, this could drive reductions in both capital and operational expenses and be commercially available by 2030 (Brown, 2019).

The ShipFC project, also part of the European Union's Fuel Cells and Hydrogen (FCH) joint undertaking, aims to demonstrate the use of ammonia as a fuel in ships using fuel cells and includes Nordic partners such as: NCE Maritime Cleantech, Eidesvik Offshore, Wärtsilä, Prototech and Equinor. The ShipFC project aims to modify the Viking Energy supply vessel to use ammonia in 2 MW solid oxide fuel cell to meet 60-70% of on-board power needs from 2024 (Equinor, 2020b). The hydrogen used to make ammonia in this project will be produced via electrolysis, by Yara.

A separate consortium of predominantly Nordic companies aims to trial ammonia fuel on the ship Color Fantasy, the second largest Ro-Ro (Roll-on Roll-off) cruise ferry in the world, owned by Color Lines (Ammonia Energy Association, 2020). Similar projects aiming to trial ammonia on larger sized ships include the NoGAPS project launched by the Global Maritime Forum based in Copenhagen.

Finally, the Zero Emission Energy Distribution at Sea (ZEEDS) project aims to develop offshore clean refueling hubs (Crolius, 2019). The unique feature of this project is that it aims to produce ammonia offshore, independently of mainland facilities, using hydrogen made by electrolysis and offshore wind. Members of the consortium include Wärtsilä, four Norwegian companies: Equinor, Aker Solutions, Kvaerner, Grieg Star and DFDS a Danish shipping company.

Table 4. Selected projects on ammonia-powered ships in the Nordic region

Acronym	Project Title	Members and/or funding agencies
ZEEDS	Zero Emission Energy Distribution at Sea	Wärtsilä, (engine manufacturer, Finland), Equinor (energy company, Norway), Aker Solutions (offshore engineering and technology company, Norway), Kvaerner (procurement and construction company, Norway), Grieg Star (ocean freight company, Norway), DFDS (shipping and logistics company, Denmark)
NoGAPS	Nordic Green Ammonia Powered Ships	Global Maritime Forum (consortium, Denmark), Nordic Innovation (funding agency), Danish Ship Finance (Denmark), J. Lauritzen (shipowner, Denmark), MAN Energy Solutions (engine manufacturer, Germany), Ørsted (energy company, Denmark), Fürstenberg Maritime Advisory (consultancy, Denmark), DNB (bank, Norway), Yara International (chemical company, Norway), DNV GL (classification agency and consultancy, Norway), Wärtsilä (engine manufacturer, Finland)
ShipFC	Ship FC Viking Energy, ammonia-powered fuel cell	NCE Maritime Cleantech (consultancy, Norway), Eidesvik Offshore (service company for the offshore oil industry, Norway), Wärtsilä (engine manufacturer, Finland), Equinor (energy company, Norway), Prototech (fuel cell manufacturer, Norway)

Electricity

Partial electrification with hybrid electric powertrain systems can improve the operating efficiency of a ship. The energy efficiency of an internal combustion engine varies based on the speed or engine load. Variability in engine loads, to cater to manoeuvring needs for example, are therefore a source of inefficiency. Hybrid electric motors can be used to charge and discharge a battery and maintain internal combustion engines operating at optimal conditions of energy efficiency. Integrating electrification into powertrains can yield similar efficiency benefits with other fuel technologies; fuel cells also operate inefficiently outside optimum design conditions and LNG engines running at part load are more susceptible to methane slip (Pavlenko *et al.*, 2020).

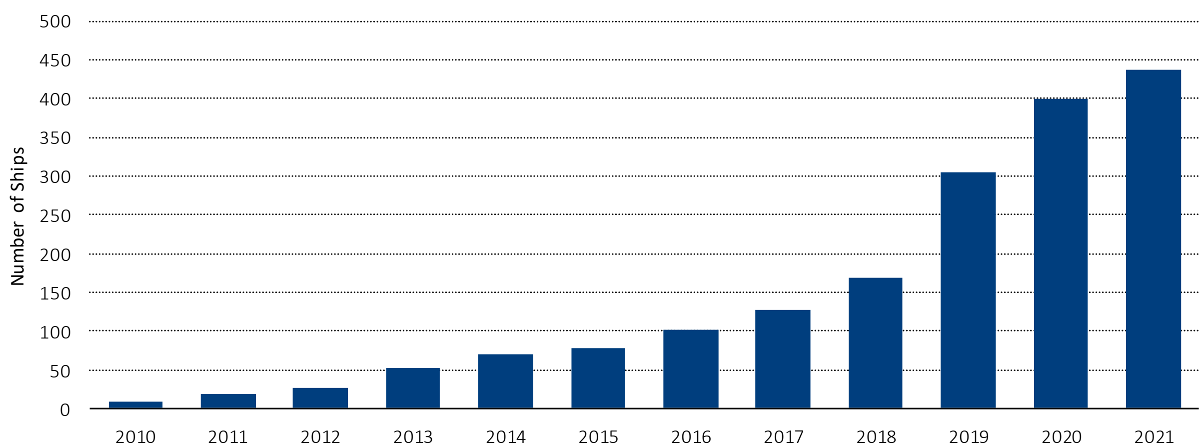
With batteries large enough, greater shares of propulsion needs can be delivered by electricity and portions of a journey can feasibly be achieved without the work of an internal combustion engine. This can enable all-electric propulsion near coastal areas and thereby reduce local air pollutant emissions. Furthermore, batteries can be charged using power from onshore electricity grids rather than solely using energy from an internal combustion engine. If the carbon intensity of grid electricity is below 500 g CO_2/kWh, then well-to-wake emissions will be lower than if using HFO[11]. Using electricity generated purely from renewable sources would make electricity a zero-carbon shipping fuel. The carbon intensity of grid electricity in the Nordic countries is approximately: 30 g CO_2/kWh (Norway and Iceland), 60 g CO_2/kWh (Sweden), 100 g CO_2/kWh (Finland) and 200 g CO_2/kWh (Denmark) (Electricity Map, 2020) meaning onshore power is likely to lead to GHG emissions reductions.

Demonstration projects

There are a growing number of hybrid electric and fully electric maritime vessels (Figure 5). There are approximately 250 battery electric/hybrid vessels either currently operating or on order globally. The Nordic region is at the forefront of electric shipping developments, with Norway alone operating 40% of global battery electric and hybrid vessels. There will be 80 electric ferries (full or hybrid) in operation in Norway by 2022 and it is reportedly profitable to replace 127 of the 180 currently in operation in Norway with battery electric alternatives (DNV GL, 2019). Similar findings apply to other Nordic countries, 70% of ferry routes in Denmark would be more profitable using electric ships (Siemens, 2016).

Electric shipping projects are already in use for several passenger car ferries, with projects such as the E Ferry “Ellen”, in Denmark (Larsen, 2020), the Norled “Ampere” in Norway and the two Forsea ferries: “Tycho Brahe” and “Aurora af Helsingborg” operating between Denmark and Sweden (Prytz, 2020). However, batteries are also being adopted in other vessel types such as offshore vessels for maintenance, cruise ferries, tugs, aquaculture boats and fishing vessels (ABB, 2019; Corvus Energy, 2020). In 2019, it was announced that the cruise ferry AIDAperla would be fitted with a 10 MWh battery system (Corvus Energy, 2019), and Equinor will require all of its 19 supply vessels to incorporate hybrid battery power and onshore power capabilities from 2020 (Equinor, 2020a).

Figure 5. Total number of ships with batteries in operation and on order globally, 2010-21



Source: Marine Battery Forum (2020).

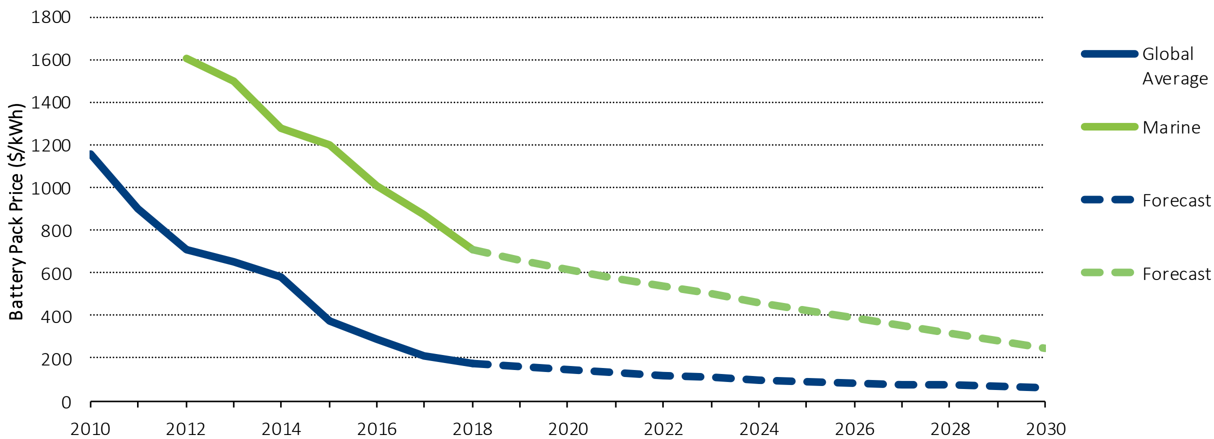
One of the largest costs in an electric vehicle is the battery, and other challenges may come from the critical nature of raw materials needed for their production, especially if batteries are adopted on a large scale in other transport modes (starting from cars).

As batteries are increasingly adopted in both ships and in other transport modes, the price of batteries is declining (Figure 6). The battery chemistries for marine batteries differ from passenger cars and are chosen primarily for longevity, and high power and energy delivery (Mjos, 2019). Early electric passenger ferry projects, such as the Swedish Movitz, produced in 2014, used Nickel-Metal-Hydride batteries. More recent ferries have instead opted for higher-performance chemistries: the E-Ferry uses graphite anode NMC lithium ion batteries (Larsen, 2020) and other common chemistries include Lithium Titanate Oxide (LTO) batteries (Echandia, 2020), a technology that is characterised by high durability, largely used in buses and now even in cars.

Raw materials guidelines are the subject of many policymaking bodies. In Europe, critical raw materials are the subject of the recently established European Raw Material Alliance (EC, 2020a). In the United States, the Office for Energy Efficiency and Renewable Energy of the United States Department of Energy and the United States Geological Survey are co-operating on the same subject (DOE, 2020). Other efforts are addressing aspects related with the carbon intensity of battery manufacturing, battery supply chain sustainability and the circular economy. A key reference in this case is the work of the European Battery Alliance (Santos Gil, 2020).

Electric batteries for marine applications currently cost considerably more than those produced for the automotive sector (Kortsari et al., 2020). This is likely due to lower opportunities for mass production and integration in ships. As the scale of battery production grows in road vehicles, costs are expected to fall. This is likely to come with positive spill-overs for batteries suitable for ships, despite a remaining gap due to higher installation costs.

Figure 6. Trends in lithium-ion battery prices by global average and marine specific categories



Source: BNEF (2019); Kortsari et al. (2020).

Shore power and cold-ironing

When ships are in port, engines and auxiliary generators are often still in use to cover energy demands. The continued burning of ship fuel produces both GHG emissions and other air pollutants in ports and surrounding towns. Approximately 11% of global maritime GHG emissions are produced from ships that are either anchored or at berth, this share is over 20% in the case of oil and chemical tankers (IMO, 2020a). Port fuel use can be reduced by plugging into onshore electricity and turning off ship generators, known as cold-ironing.

Nordic countries were frontrunners in the installation of shore power facilities in ports. The port of Stockholm already provided shore-side electricity in the 1980s, followed by the port of Gothenburg in the 1990s. Various other Nordic ports, including the Finnish ports of Kemi, Kotka and Oulu, installed shore power facilities in the 2000s. Many of the major Nordic ports now provide shore power facilities, often for regular ferry connections, where it is relatively easy to make sure that ships and terminals are equipped at the same time. For example, the port of Stockholm provides shore power for the regular ferry connections of Viking Line, Silja Line and Polferries. The port also offers grants of SEK 1 million (EUR 97 000) to shipping companies that want to equip their vessels with shore-power connections.

Cruise ships are also increasingly connecting to shore power. They use a lot of energy at berth, so generate large amounts of local air emissions to the port-city. The high-energy consumption is also a challenge as it requires powerful shore power facilities. In order to be able to provide shore power to three cruise ships at the same time, the Norwegian port of Bergen and the renewable energy company BKK have established a joint company, called PLUG AS, which will build the largest shore power facility in Europe.

The emergence of electric vessels for coastal shipping and ferries has gone hand-in-hand with the need for electric charging in ports. Norway has been pro-active in this area, funding both electrification of ships and shore-side electricity in ports, resulting in over 60 Norwegian ports that received funding for shore power or electric charging facilities in the past five years (Enova, 2020a).

To date there are approximately eighty large ports (four of which are in Norway) with onshore power infrastructure worldwide, with the majority in Europe and the United States (IEA, 2020d). The rollout of shore power infrastructure has been promoted in both of these regions by regulations such as the EU Directive on the Deployment of Alternative Fuels Infrastructure and the California Air Resource Board (CARB) Ocean-Going Vessels at Berth Regulation. The CARB regulation requires ship operators to reduce on-berth emissions by 80% by 2020 while the EU requires ports to install infrastructure by 2025 (T&D Europe, 2015; CARB, 2018). China also has introduced legislation requiring new port terminals to provide onshore power infrastructure and promoting its use in ships (IEA, 2020d).

Cold-ironing can lead to financial savings for ship operators since electricity generally costs less than marine fuel, depending on the capital expenditure needed to make use of onshore power. Reducing ship emissions with cold-ironing can have societal cost benefits from health improvements; typical payback periods accounting for societal benefits range between seven and thirteen years (Ballini and Bozzo, 2015; Innes and Monios, 2018).

The widespread adoption of cold-ironing faces several challenges. The voltage and frequency of grid electricity varies from country to country, as do the electricity requirements of ships. Frequencies can be either 50 or 60 Hz and voltages can vary from 110 V to 11 kV (Zis, 2019). This lack of standardisation means power conversion equipment needs to be installed by port authorities to ensure onshore power is compatible with ship requirements.

IEC, ISO and IEEE have developed standards that set requirements for shore-side electricity supply systems, capable to guide specifications for both cold-ironing at berth and the charging of electric ships. They cover shore distribution systems, shore-to-ship connection and interface equipment, transformers, semiconductor/rotating converters, ship distribution systems and control, monitoring, interlocking and power management systems. The general safety of high voltage and low voltage shore connection systems are covered, respectively in the IEC/IEEE DIS 80005-1 and IEC/IEEE DIS 80005-3 standards. The IEC/IEEE DIS 80005-2 standard deals with data communication requirements for monitoring and control of these connections (DNV GL, 2018). These are complemented by the IEC 60309 standard, defining the characteristics of low-voltage shore connection systems (including connectors), and most relevant for recreational boats and/or plugging on-board appliances.

The IEC 62613 has a similar function for high voltage shore connection (HVSC) systems. Its scope includes only alternate currents (50/60 Hz), intensities not exceeding 500 A and rated operating voltages not exceeding 12 kV (i.e. 6 MW of power). Its focus is on utility connection for the provision of shore power. The current set of standards does not include a harmonised solution for e-ferries. This matches the observation that currently, e-ferries operate use a variety of case-specific charging connections. While the IEC/IEEE DIS 80005-3 promotes interoperability and encourage ship operators to install equipment for large ships, there is room to make progress on standardisation developments suitable for e-ships. Greater harmonisation for e-ferry connections and onshore power facilities could provide better certainty to both port authorities and ship operators, enable cost reductions for the design of the components needed for charging operations and it could be an important enabler of e-ferry deployments at a larger scale, including beyond the Nordic region.

Further considerations include the limited space in ports needed to provide charging systems (Innes and Monios, 2018) and logistics associated with managing berth availability, a key determinant of port competitiveness (Yeo, Roe and Dinwoodie, 2008), to ensure berths equipped with onshore power facilities are available for ships intending to make use of them.

Port authorities also face barriers to installing onshore power equipment if they are uncertain about the number of ships that are likely to use grid electricity. Ship operators face similar challenges when investing in charging equipment if they are uncertain about the availability of suitable onshore power facilities. This uncertainty can differ by ship and port; a port receiving small ships with relatively constant schedules may have greater certainty about onshore power requirements than ports receiving tankers with less-defined schedules dictated by changes in spot market prices (Zis, 2019).

What could be the best fuels to decarbonise shipping?

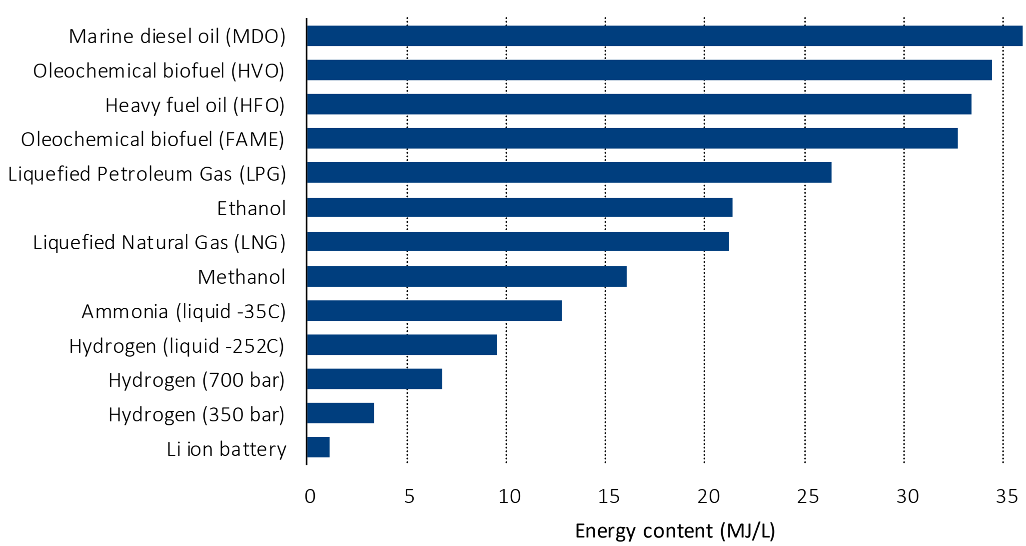
Making the right choice between the possible fuels and energy vectors to steer maritime transport on an energy efficient and low-carbon route, is a challenge for policy makers. Four broad factors can help to narrow down the choice to the most promising solutions: the energy density of fuels, their GHG emissions intensity, the potential to scale up the production of the fuel in time to have a meaningful impact on climate change, and finally cost prospects. Each of these four factors can place constraints on the viability of an individual fuel. Energy density is the first requirement for long distance transportation, low GHG emissions are essential to meet climate goals, production at scale is indispensable to replace large volumes of oil-based fuels and cost minimisation is a crucial requirement for any economical assessment.

Energy density

The number of sustainable fuel options for maritime transport can be narrowed down by firstly considering their energy density. The petroleum-based fuels that account for the majority of energy use in shipping today, have the advantage of having a high energy density, as 33 MJ of energy are released per litre of fuel burnt. Almost all alternative fuels proposed to date that can reduce air pollutant and greenhouse gas (GHG) emissions have a lower energy density. This will mean that larger fuel storage tanks are inevitable for large ships, which can either lead to lower space for cargo or range limitations for different fuels.

The energy storage solution with the lowest energy density is lithium ion (Li-ion) batteries in electric ships, which are two orders of magnitude less energy dense than HFO, even accounting for the better efficiency of electric motors with respect to combustion engines. This low energy density restricts ships running purely on electricity to short routes (<200 km). Whilst numerous, these account for only a small fraction of global maritime GHG emissions.

Figure 7. Energy density of different fuel options (MJ/L)



Compressed hydrogen is likely to face similar restrictions, as its energy density is between 3.3-6.8 MJ/L, depending on the storage pressure. Conversely, a recent assessment focused on ships using liquid hydrogen, which has an energy density of 8.5 MJ/L, showed that they could feasibly cover the majority of journeys across the Pacific, while certain routes would require alterations (Mao et al., 2020). As other alternative shipping fuels have an even higher energy densities, it is unlikely that they will face fundamental physical limitations to trip distances, though route alterations and intermediate refuelling may be required for some fuel options.

Greenhouse gas emissions reduction potentials

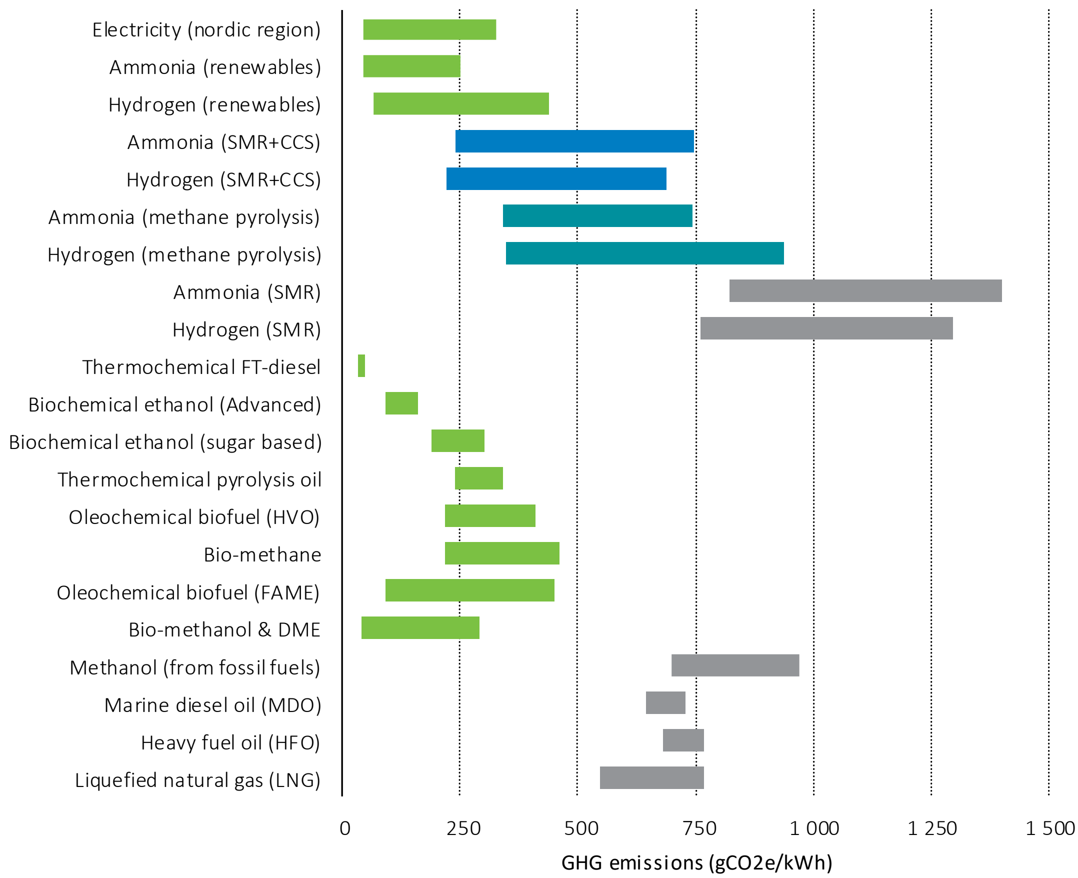
One of the main motivations for changing fuels is to reduce GHG emissions. The GHG intensity of fuels is therefore a major factor when assessing the viability of different fuel options. To evaluate GHG emissions, fuels are best compared on a life-cycle or well-to-wake basis. These two methods account for both the emissions produced when burning a fuel within a ship's powertrain, and the emissions associated with fuel production from primary energy resources and fuel transportation. The fuels introduced in the previous section differ significantly in GHG emissions intensities due to the different sources of energy and the number of conversions needed to produce useable fuels.

Figure 8 shows the range of well-to-wake GHG emissions produced for each kWh of propulsion work in a ship. These estimates account for both the emissions associated with fuel production and their use. Key points include:

- Electricity generated using the electricity available in the Nordic region can offer a low-carbon option compared with fossil fuel alternatives.
- Biofuels have the potential to reduce GHG emissions if produced through advanced processes that have a high reliance on waste-based biomass feedstocks, low impacts on land-use change and a low reliance on fossil fuels, though supply may be limited and demand is likely to face competition from other sectors and transport modes.
- Hydrogen, ammonia and synthetic hydrocarbons/electrofuels also offer low-carbon alternatives if they are produced using renewable electricity, with carbon capture and storage of fossil energy resources or with renewable forms of carbon (from biomass or direct air capture).
- Substituting HFO for hydrogen, ammonia or electrofuels (including methanol) produced by steam methane reformation without carbon capture and storage would therefore lead to significant increases in GHG emissions.
- Fossil LNG has a limited potential to deliver GHG emission reductions due to methane slip and upstream methane leakage. Methane slip remains relevant for bio-methane, despite its significant GHG emission savings. Unless these challenges are suitably addressed, LNG is unlikely to play a role in meeting the climate change mitigation targets brought forward in the Paris Agreement, which have been incorporated in the national ambition of all Nordic countries (as outlined in chapter 3) and reflected in the initial strategy on GHG emission reductions of the IMO.

Theoretically, a switch to fossil-based versions of hydrogen, ammonia, methanol and LNG could provide the infrastructure to enable a transition to low-carbon versions of these energy vectors. Nevertheless, their poor performances when produced from fossil resourcesand lack of carbon capture and storage comes with important risks for a decarbonisation pathway.

Figure 8. Well-to-wake greenhouse gas emissions of different fuel options per kWh of shaft work



Note: SMR = synthetic methane reforming; CCS = carbon capture and storage; FAME = fatty acid methyl ester; DME = dimethyl ether. All estimates use greenhouse warming potentials over a 100-year timeframe (GWP 100).

Source: ITF analysis based on Balcombe *et al.* (2019); Parkinson et al. (2019); Kortsari et al. (2020); Pavlenko et al. (2020) [12]

The evidence stemming from life-cycle assessment of fuels highlights policy challenges for the IMO's Energy Efficiency Design Index (EEDI). The current formula used for calculating the EEDI of ships is based on the ratio of direct CO_2 emissions to transport work needed to move the ships (GloMEEP, 2020). Though this calculation method offers incentives to deploy LNG (and in future methanol, ammonia and other alternative fuels) it does not yet offer a reliable GHG emission mitigation capacity.

Integrating well-to-tank and methane slip emissions into the EEDI calculation and switching to GHGs/CO_2 equivalents rather than just direct CO_2, are key priorities to allow maritime transport to effectively deliver on climate change. An alternative would be to focus the EEDI purely on energy efficiency, and complement it with effective instruments targeting reductions in the carbon intensity of fuels. Examples of this are carbon pricing, regulatory mandates and low-carbon fuel standards, or integrating a well-to-tank emission accounting framework similar to those that are under development for international aviation.

The potential to scale-up

To have a substantial impact at reducing emissions from the shipping sector, alternative fuels need to be rapidly deployed at scale. A number of factors influence the scalability of a fuel; these include technology readiness, the availability of the resources and feedstocks needed to produce a fuel, and the ability to make use of existing infrastructure.

Technological readiness

The increasing number of projects with electric ships show it to be a rapidly maturing technology, likely to be deployed extensively on short-distance routes in the near future. Conversely, many of the alternative fuels needed for longer distance shipping are at a lower level of technological maturity. Technological maturity is an issue for a number of advanced biofuels, in particular those based on the integration of biomass resources in refining and others included in the thermochemical and biochemical conversion pathways.

Technologies required for renewable production of hydrogen, ammonia and synthetic hydrocarbons have not yet been tested at large scale. This limited technological maturity is coupled with a limited development of standards allowing vessels to use fuels and operate safely and smoothly across different administrative borders.

Similarly to LNG, the adoption of new fuels in shipping such as hydrogen and ammonia will require amendments to existing regulations to ensure safe use. The most relevant being to the IMO IGF Code. Until these are approved, the adoption of these fuels will likely remain limited to demonstration projects. Interim guidelines for the safety of ships using methyl or ethyl alcohol were initially proposed in 2016 and are currently pending approval by the IMO Maritime Safety Committee and were delayed by the Covid-19 pandemic (IMO, 2019). Other work packages in the pipeline at the IMO before 2023 cover the use of fuel cells in ships and the approval of liquefied petroleum gas (LPG).

Guidelines on the use of ammonia and hydrogen as shipping fuels are not scheduled before 2023 but will likely be considered following the results of demonstration projects in the mid 2020’s. Guidelines on the use of ammonia as a fuel can make use of existing standards covering its transport and handling. In contrast, amendments to the IGF for hydrogen are likely to be more complicated since there are limited existing guidelines covering its handling and transportation as a fuel, and these would have to be developed in parallel.

Important developments to technical regulations and standards to boost scale-up include: the characterisation of Guarantees of Origin defining the carbon content of the fuels, the installation and approval of on-board energy storage and propulsion systems for vessels, and the development of interfaces and protocols for safe refuelling operations when using hydrogen and ammonia as the main shipping fuel. Issues still exist with scaling-up the electrification of ships given the need to complete the work started in the IEC, ISO and IEEE framework onshore connection systems with power requirements up to 1 000 kVA and the heterogeneity of the systems used on ferries, despite the Nordic leadership in this area.

Resource availability

The availability of the resources and feedstocks needed to produce a fuel can place constraints on its potential to scale-up and displace petroleum-based fuels.

Biofuels face resource constraints relating to the land area required to produce a sufficient quantity of fuel and the supply of sustainable forms of biomass and waste streams needed as feedstocks. Some studies refer to a primary bioenergy supply availability for 2030-60, in the range of 110-150 EJ overall and estimate an 30-80 EJ allocation to the transport sector (IRENA, 2014, 2018; IEA, 2017b, 2017a; IEA and IRENA, 2017; ETC, 2018). These studies acknowledge potential constraints on the supply of sustainable biomass. These figures are broadly consistent with indications available in (Creutzig et al., 2015), of a sustainable technical primary biomass potential up to 100 EJ, despite a wide range of sustainable biomass availability assessments in earlier work. They indicate that sustainable biofuels could (technically) be available at a scale. Despite competition across different end-uses, this would enable them to provide a significant and meaningful contribution in terms of energy end-use: up to half of the primary biomass potential. This amount could be further enhanced by the integration of low-carbon hydrogen and biogenic carbon from biomass for the production of PBtL.

There are large regional differences in the availability of biomass resources. With its large forestry sector, the Nordic region may be in the position to ensure that biofuels contribute in a significant manner to its shipping fuel mix. This availability of biogenic feedstocks may be further improved if integrated with solutions using biomass resources enriched with low-carbon hydrogen such as PBtL pathways.

The large primary energy requirements of fuels such as low-carbon hydrogen, ammonia and synthetic hydrocarbons may limit their potential to scale-up. Producing a fuel requires converting energy from a primary form (e.g. crude oil, coal or energy from solar and wind) into a usable final energy vector (e.g. hydrocarbons, alcohols, hydrogen or ammonia). This final energy vector is then converted into useful propulsion work to move vessels using an electric motor, paired with a fuel cell or battery, or an internal combustion engine. The series of conversions necessary to convert primary energy into shaft work are part of the energy chain. Generally, the more conversions of energy from one form to another, the greater the energy losses.

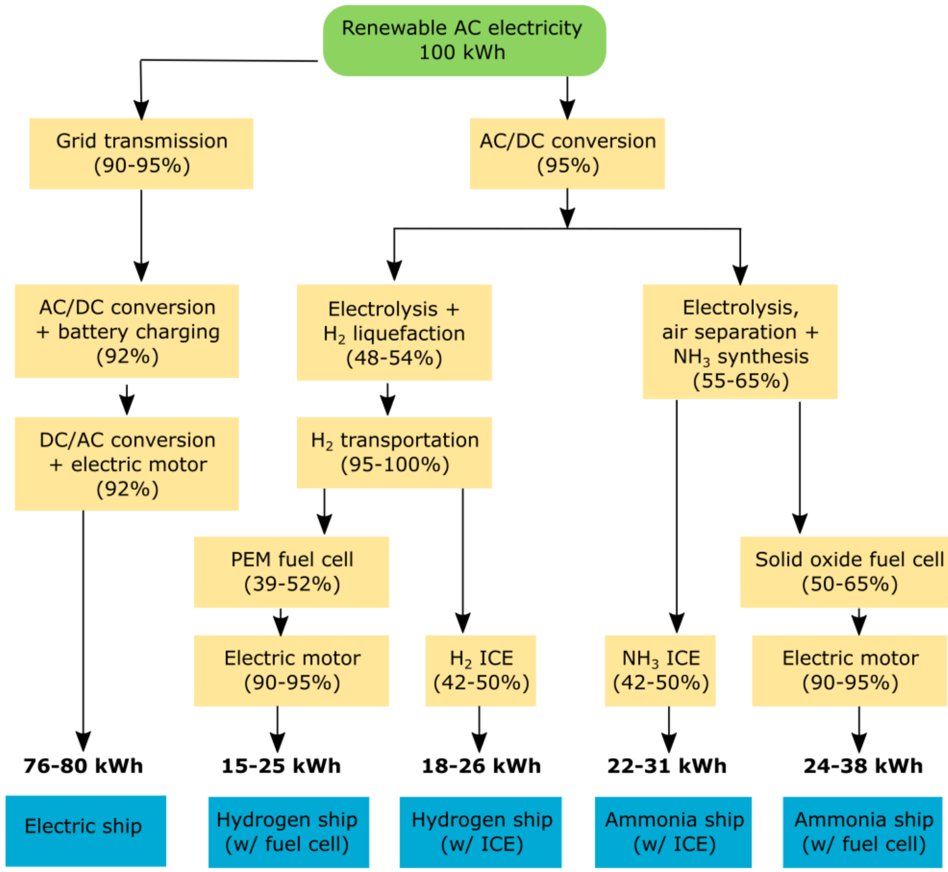
For example, producing and directly using hydrogen in ships requires a significant number of conversions, including:

- Synthesis from electrolysis or production from other low-carbon pathways, requiring carbon capture and storage.
- Compression to enable gaseous storage, liquefaction to enable liquid storage or conversion into an alternative storage medium such as ammonia.
- Use in a fuel cell or internal combustion engine.

Inevitably, each of these steps are associated with thermodynamic losses that translate into large requirements for the primary energy needed (e.g. renewable electricity) to produce a given quantity of hydrogen. This raises challenges to the scalability of hydrogen as a fuel. Other low-carbon synthetic fuels have similar constraints regarding production inefficiencies but have comparative advantages due to lower losses in fuel transport and handling.

Figure 9 provides an example of the energy contained in hydrogen or ammonia that can be produced per unit of renewable electricity, accounting for losses occurring in processes like electrolysis, other fuel production steps, fuel handling for transport and distribution purposes and final use. With 100 kWh of renewable electricity, only a quarter can be converted into shipping fuels such as hydrogen or ammonia and the remainder is lost. This means that satisfying shipping energy demand for final energy in the form of ammonia or hydrogen would require roughly four times as much energy in the form of renewable electricity. Using renewable electricity in a battery electric ship on the other hand is far more efficient, as there are fewer conversions of energy in the chain. The main barriers for battery electric ships are the ability to store a sufficiently large amount of energy in the battery for long voyages.

Figure 9. The energy chains for powering ships with renewable electricity



Note: AC = alternating current; DC = direct current; ICE = internal combustion engine; PEM = proton exchange membrane. See note 13 for further details.

Meeting long-term energy demand in shipping using solely ammonia would require global production to triple from current levels, to reach around 500 Mt per year by 2050, approximately thirty times the volume of ammonia currently traded internationally (IEA, 2019b). Such a development would also need to manage potential indirect competition for ammonia supply (and price developments) with food production, since ammonia is largely used for fertiliser production (Brightling, 2018). To significantly reduce the carbon intensity of shipping, hydrogen production would have to shift from being almost completely reliant on the reforming of fossil fuels, to production via electrolysis using low-carbon electricity instead.

Stock replacement effects and requirements for new fuel distribution infrastructure

The lifetimes of assets present a final barrier to the speed with which an alternative fuel technology can be adopted and scaled-up. New technologies available today will take decades to be adopted by the full shipping fleet due to the long lifetime of ships (roughly 25 years). This effect can be partly mitigated by retrofits and ensuring flexibility of existing engines and fuel distribution systems to future fuels. The development of brand new infrastructure, with bespoke requirements such as fuel handling and distribution, can lead to chicken-and-egg investment risks, and therefore costs increases.

Cost prospects

Heavy fuel oil (HFO) and marine diesel oil (MDO) are the most common fuels in marine shipping and have less restrictive quality requirements than transport fuels in other applications. This means marine fuels are generally cheaper than petroleum-based transport fuels for road and aviation. Alternative fuels aiming to displace today's shipping fuels have to compete both on the cost of producing the fuel and the additional costs associated with the installation of fuel distribution infrastructure.

Fuel production costs

Advanced biofuels, based on cellulosic feedstocks have greater barriers to cost reductions than other options. In the Nordic region, this is an issue that can be partly mitigated by the well-established industry that is already exploiting and managing forest resources, e.g. for pulp and paper production and the progress already made by companies like Neste and UPM in Finland (Neste Corporation, 2015; UPM, 2020b).

For hydrogen, ammonia and synthetic carbon-based fuels, production via electrolysis is likely to remain more expensive than pathways using fossil fuels for the near-to-medium term, unless renewable electricity is available in forms that enable high enough electrolyser load hours (around 4 000 hours per year) and at low cost per MWh (USD 10-40/MWh) (IEA, 2019b). Production costs for ammonia via electrolysis are lower than those for synthetic hydrocarbons: current values are estimated at USD 140/MWh (with electricity at USD 50/MWh at 3 000 full load hours for hydrogen electrolysers), possibly falling to USD 70/MWh with lower electrolyser costs and electricity at USD 25/MWh (IEA, 2019b). The cost of ammonia from steam methane reforming today is approximately USD 50/MWh (IHS Markit, 2020).

Fuel infrastructure costs

The costs related to developing dedicated infrastructure for fuel transportation, storage in ports and distribution are integral to fuel production pathways. Here, alternative fuels can be distinguished between those that can be blended with petroleum fuels and make use of existing infrastructure with only minimal alterations and others that require significant new infrastructure and fuel handling procedures.

Drop-in liquid hydrocarbons, including advanced biofuels and synthetic hydrocarbons/electrofuels that are compatible for direct blending with petroleum-based fuels, have a significant advantage compared with other alternative fuels. This is because they can exploit the existing transport, storage and distribution infrastructure.

Since the Nordic region has the densest network of LNG bunkering facilities in the world (many of which are recent in line with the uptake of LNG-fuelled vessels), [14] biogas can also be considered a "drop-in fuel" than can make use of existing fuel distribution infrastructure. Legislative frameworks such as a green certificate mechanism can enable this, for example allowing crediting biogas injected to the grid to different end-uses. In Denmark there are already 50 biogas plants that feed into the gas network and are expected to deliver 20% of natural gas demand by the end of 2020 and 30% by 2023 (Evida, 2020). However, reaching high shares of biogas use in the current gas grid can face challenges in terms of available volumes.

Conversely, new fuels such as methanol, hydrogen and ammonia require the mobilisation of new infrastructure investments, which is one of the main challenges to the widespread adoption of these low-carbon shipping fuels (Krantz, Søgaard and Smith, 2020).

The challenges posed by the need to develop new transport, storage and bunkering facilities, can be effectively illustrated by the case of LNG. The significant investments required to install bunkering facilities have slowed the fuel's adoption, even though the operational cost of LNG is even lower than that of HFO.

The lack of certainty concerning the availability of LNG bunkering facilities creates challenges for shipowners wanting to invest in LNG-fuelled ships. This matters for costs because the financial viability of fuel storage and distribution infrastructure is likely to be highly dependent upon the utilisation rates. If utilisation rates are not sufficiently high there is a risk of stranded assets. The challenges of developing new infrastructure are exacerbated by the fact that LNG has a lower volumetric energy density than HFO, meaning LNG ships require more frequent bunkering from a greater number of bunkering facilities. In the case of cargo ships, LNG tanks are limited in size in order not to consume too much of the space dedicated to cargo.

These challenges are likely to apply for methanol, hydrogen and ammonia, especially given their even lower energy density. This calls for strategies to mitigate these risks. Fuel storage and distribution infrastructure can be increased by diversifying its use with other sectors, for example by leveraging industry clusters to ensure that large enough volumes for hydrogen supply can be secured by an appropriate demand. Overcoming the barriers to the installation of fuel distribution infrastructure can be facilitated by international co-ordination between ports for maritime services. The lowest risks for the deployments of fuel distribution infrastructure are likely to occur in ports with ships serving local routes with predictable demand. Larger vessels, moving over more diverse international routes, may face greater difficulties shifting to hydrogen or ammonia if these are not deployed first on local movements, unless they operate on fixed routes. An evolutionary scaling up, of both local routes and fixed international shipping journeys (such as liners) may provide an avenue to mitigate investment risks in the deployment of fuel distribution infrastructure for low-carbon gaseous fuels.

Finally, not all gaseous fuels have the same characteristics. Hydrogen, in particular, is significantly more difficult to handle than LNG or ammonia, due to the need for very high pressures to store significant amounts of energy in gaseous form and very low temperatures to do so in a liquid state. Additional complexities include its tendency to cause accelerated embrittlement of metals and the fact that it can be highly explosive. These challenges mean the additional costs due to transport, storage and distribution infrastructure are likely to be higher for hydrogen than for ammonia. It also means that the challenges and risks posed by the low utilisation of fuel storage and distribution infrastructure in its initial phase of deployment will place higher risks on the use of low-carbon hydrogen as a shipping fuel than they will do on low-carbon ammonia.

The fuel storage and distribution costs, coupled with the relatively high production costs of other synthetic hydrocarbons/electrofuels, indicate that ammonia may be better placed to emerge as a low-carbon shipping fuel. Advanced biofuels may have higher production costs than ammonia, but they have the relative advantage of low barriers and risks on fuel storage and distribution and should therefore also remain a possible candidate for the evolution of maritime transport towards net zero emissions. In addition, the requirement of a pilot fuel for ammonia indicates that sustainable and low-carbon diesel equivalents (indeed including advanced biofuels) could be required to attain deep decarbonisation goals in the shipping sector.

Given the uncertainties and investment risks, flexibility in the use of different fuels is likely to be a key feature for new ships. Internal combustion engines (ICEs) are likely to remain the powertrain of choice in the near-to-medium term due to their flexibility for burning alternative fuels, existing widespread use and relatively high thermal efficiency. This is despite the fact that dual-fuel engines are often less optimised for a specific fuel, and can lead to marginally lower efficiencies. Retrofitting existing ships to be able to use lower carbon fuels is also likely inevitable part of the solution to deliver the pace of decarbonisation required to meet IMO climate change goals (Bullock et al., 2020).

Electrification of ships is not only best placed for short distance, but it also presents opportunities for evolutionary reductions in maritime emissions. Cost developments indicate that onshore charging systems will become increasingly available. Modular designs allow battery packs to be easily replaced, allowing battery capacity to be added as cell densities improve over time. The flexibility offered by hybrid electric powertrain systems is likely to reduce investment risks and strengthen the attractiveness of this option for powertrain developers.

The most relevant technology pathways to decarbonise shipping

The adoption of technologies and alternative fuels is essential to meet IMO decarbonisation goals. Energy efficiency measures on both new and existing ships are technologically ready, cost effective and an essential component of this. In addition to reducing the emissions intensity of ships, energy efficiency can help to temper additional costs associated with future low-carbon fuel options. However, sustainable low-carbon fuels will also be required to displace existing fossil fuels to sufficiently decarbonise maritime trade.

Electric ships can be highly effective at reducing ship emissions and have been deployed successfully as ferries in the Nordic region. However, the low energy density of batteries places fundamental physical limitations on the potential of electric ships, constraining them to short-distance journeys. Compressed hydrogen likely faces similar barriers.

The use of LNG as a shipping fuel can help to reduce NO_X, SO_X and other air pollutant emissions. Using LNG can also lower direct CO_2 emissions produced on board ships by approximately 20%. However, fugitive emissions from methane slip in engines and throughout the upstream supply chain of natural gas mean the use of LNG risks having higher life-cycle GHG emissions than the continued use of existing maritime fuels, unless these fugitive emissions can be effectively brought under control.

The suitability of methanol as a ship fuel is highly dependent on the method in which it is produced. Methanol produced by fossil fuels would have a higher GHG emissions intensity than the continued use of existing maritime fuels. The combustion of methanol will always produce CO_2 emissions, meaning it is essential that it be produced by a process leading to net negative emissions such as a biogenic source of carbon or CO_2 from DAC. The latter is unproven at scale and likely entails infeasible energy requirements.

Advanced biofuels, in particular liquids that can use existing fuel infrastructure, can play a role in reducing petroleum-based fuel demand and GHG emissions. These are likely to face competition from other transport modes and sectors (namely aviation) and require a solid regulatory framework to ensure that they can be supplied at scale in a sustainable manner. Integrating biomass supplies with renewable hydrogen can maximise fuel output from biogenic carbon sources. This is especially relevant in the Nordic region, given the available biomass resources from forestry and the competitiveness of wind and hydro electricity generation.

The use of liquid hydrogen and ammonia as fuels in large ships could offer low-carbon alternatives, but remains at demonstration phase. Hydrogen production by electrolysis and renewable energy is likely the lowest carbon pathway, but requires renewable generation at a large scale to reduce costs. These costs are likely to remain significant due to the losses in the energy chain. Hydrogen production from steam methane reforming with carbon capture and storage could help to scale-up low-carbon hydrogen production, but carbon capture must be effective and financially viable at storing carbon for a long period of time. Hydrogen produced from methane pyrolysis could simplify carbon storage by producing solid carbon, but remains at a lower level of technological development. Importantly, if hydrogen and ammonia are to be used as shipping fuels it is essential that a low-carbon production route is used. The use of hydrogen or ammonia produced using unabated SMR as shipping fuels would be more detrimental to the climate than the continued use of HFO.

For greater ease of transport, storage and distribution, as well as using existing international trade routes, ammonia offers an advantage over hydrogen, but it also comes with the likely requirement of a pilot fuel. If ammonia and/or hydrogen were to be adopted at scale, it will be important to verify (and certify adequately) the production methods used to create the fuels, particularly as production by traditional steam methane reformation is likely to remain cheaper than lower carbon alternatives.

The Nordic region is playing a pivotal role in advancing the adoption of low-carbon technologies through a large number of demonstration projects and research programmes. These projects are important to overcome technical barriers and highlight possible alternatives to existing fossil fuels. They can also accelerate the regulatory and safety legislation necessary to deploy new technologies at scale under the short timeframes required to tackle climate change.

Nordic region policies for the decarbonisation of the maritime sector

Nordic countries have adopted legislation to reflect their climate commitments under the Paris Agreement. Countries are bound to targets set under the Initial IMO Strategy on reduction of GHG emissions from ships (IMO, 2018). In December 2019, the Scandinavian countries signed the Niulakita High Ambition Declaration on Shipping along other IMO member countries. Signatory parties commit to peak GHG emissions from international shipping, start their decline before 2023 and adopt short-term measures consistent with a reduction of global CO_2 emissions by at least 40% by 2030 and at least 70% by 2050 compared to 2008.[15]

Most Scandinavian coasts are included in Emission Control Areas (ECA) since January 2015. Established under the International Convention for the Prevention of Pollution from Ships, MARPOL Annex VI, their aim is to limit the sulphur (SO_x) content of ship fuels to 0.1% in the Baltic and North Seas. To date, environmental strategies for the shipping sector have mainly focused on air pollution control (SO_x and NO_x) rather than the reduction of greenhouse gases.

In addition to IMO regulation, some Nordic countries have taken unilateral action and committed to more ambitious climate targets. Ports, national shipping associations or companies have volunteered their own targets for carbon neutrality.

Table 5. Greenhouse gas reduction targets

Country	GHG reduction targets (overall)				GHG reduction targets (transport)		
	2030	2040	2045	2050	2030	2045	2050
Denmark	70% (1990)	-	-	Low-emission society	-	-	-
Finland	40% (1990)	Carbon neutrality*	-	80% (1990)	50% (2005)	-	-
Iceland	40% (1990)	Carbon neutrality	-	-	-	-	Phase out fossil fuels
Norway	40% (2030)	-	-	80-95% (1990)	50% *[Shipping]*	-	-
Sweden	63-75% (1990) *[Sector-specific]*	-	85% (1990); Zero net emissions	-	70% (2010)	Climate neutrality	-

Note: The year in brackets is the reference year, or level compared to which emissions must be reduced.
*By 2035

Source: ITF based on: Danish Energy Agency (2020), Finnish Ministry of the Environment (2020b), Government of Iceland (2020a), Government of Norway (2018), Swedish Environmental Protection Agency (2019).

The following sections summarise the Nordic countries' binding and non-binding climate targets for the overall economy and the transport sector, where available. Norway, to date, is the only Nordic country who has specified a separate emissions reduction target for the shipping sector.

Denmark

The Danish climate law was passed by parliament in 2014 (Danish Energy Agency, 2020). It initially included a 20% emissions reduction target until 2030 compared to 1990 levels and:

- established a council on climate change (independent and academically based) in 2015
- commissioned an energy policy report to be submitted by the government to the parliament every year
- required new national climate targets to be established each year.

In June 2020, the Danish parliament passed a new climate act replacing the 2014 Act and committed to reach a 70% reduction below its 1990 emissions by 2030. New legally binding targets will be set every five years, with a ten-year horizon (Danish Ministry of Climate Energy and Utilities, 2019). The 70% reduction target excludes international shipping. To date, the government has not set a sector-specific target for domestic emissions from maritime transport.

The Act includes annual parliamentary assessments of the government's action towards meeting the targets. It also commits the government to report separately on Denmark's impact on international emissions, including those pertaining to international shipping. In addition, the government is obliged to produce an annual global strategy to harmonise its climate policies with Denmark's foreign, development and trade policies and strengthen its position as an international driver in climate policy (Danish Ministry of Climate Energy and Utilities, 2019).

The Danish Climate Council (Klimarådet) assesses climate policies and sets recommendations. The budget of the Council was doubled under the 2020 Act and its political power strengthened. The present Act was criticised for not including a number of recommendations from a recent report by the Danish Climate Council (Klimarådet, 2020), and for allocating insufficient funding to reach the 2030 target (The Local, 2020).

Part of the new measures are two artificial wind power islands which will be put into operation by 2030 totaling 5 GW. The government specified that excess power from new wind farms are to be converted using Power-to-X technology (the enabler of hydrogen, ammonia and synthetic fuels from renewable electricity), benefitting future fuel needs of the maritime transport sector (Danish Ministry of Climate Energy and Utilities, 2020).

The 2018 Danish Energy Agreement committed Denmark to 50% renewable energy by 2030 (Danish Ministry of Climate Energy and Utilities, 2018). It allocated DKK 240 million funding annually over 20 years for expansion of biogas and other green gases for transport and industrial processes and DKK 100 million annually from 2020-24 to green solutions in the transport sector, including public transport by sea.

The Danish Shipping industry intends to become carbon neutral by 2050, without the use of emissions offsets. Commercial operation of the first ocean-going zero-emission vessel is planned before 2030. The climate strategy representing Denmark's shipping industry, Partnership for a Blue Denmark (2020), consists of six elements: sharing performance data for voyage optimisation, reducing waiting times in ports, a partnership for zero-emission pilot vessels (ShippingLab), establishing a maritime research centre of excellence, pushing for the creation of a global innovation fund, and co-ordinating efforts to attract EU research funds. It also provides 15 recommendations for government covering energy efficiency, ports and shortsea shipping, green fuels, and stronger climate diplomacy and cooperation (Partnership for a Blue Denmark, 2020).

The private shipping sector is also committing to lower emissions. In 2018, the Danish company Maersk, the largest container shipping company in the world, announced its own target of making its fleet carbon-neutral by 2050 (Maersk, 2019b) and in 2020 it announced the set up a new research centre intended to lead the way for decarbonising shipping (Maersk, 2020).

Finland

The Finnish Climate Change Act (609/2015) began on 1 June 2015. According to the Act, Finland must reduce its overall GHG emissions by at least 40% by 2030 and at least 80% by 2050 compared to the 1990 level. The Act also lays down provisions on a climate policy planning system and on monitoring the achievement of climate objectives (Finnish Ministry of the Environment, 2020b).

The government aims to achieve carbon-neutrality by 2035 (Finnish Ministry of the Environment, 2020a). That is why the present Climate Change Act will be reformed in 2020-21 to achieve a balance between emissions and sinks by 2035. Other strategies to be updated in 2021 include the Climate and Energy Strategy and Medium-term Climate Change Policy Plan (KAISU) (Finnish Ministry of the Environment, 2017). These are part of the overall climate policy planning system.

The Climate Change Act obliges the Government to publish an annual climate report on the trends in emissions and the achievement of emissions reduction targets included in the medium-term plan (Cederlöf and Siljander, 2020). Finland also intends to halve transport emissions by 2030 compared to 2005 levels under this medium-term plan (Finnish Ministry of the Environment, 2017). However, this plan does not specify actions taken in the maritime transport sector, focusing mainly on road transport instead.

A transport-specific climate strategy is underway. The working group that prepares the decision-making basis for a national roadmap for fossil-free transportation began in November 2019 (Finnish Ministry of Transport and Communications, 2019). The roadmap will set specific emission reduction commitments for the various transport sectors, and identify the key policy measures and their costs. A first version will be submitted for public consultation in September 2020. The working group will identify policy measures to halve the GHG emissions of domestic transport by 2030 compared to 2005, and make transport emission-free by 2045 at the latest. Based on the work of the group, the Ministry of Transport and Communications will prepare a roadmap that identifies both the key measures and their costs, including impact assessments.

At the beginning of 2020, the Prime Minister's Office appointed an inter-ministerial steering group to prepare a Maritime Policy Action Plan set to be completed in the first half of 2021 (Finnish Prime Minister's Office, 2020). The action plan will be based on consultations with Finland's maritime stakeholders.

The Port of Helsinki has already adopted specific targets that include a 25% reduction in vessel emissions through shore-power capabilities in nine other Finnish ports, availability of alternative fuels, and an enhanced environmental programme targeted at ships. The Port of Helsinki aims to be carbon neutral in terms of its own emissions by 2035. It will focus on the reduction of emissions of vehicles entering ports, as well as machinery in the port area.

Iceland

Iceland aims to be carbon neutral by 2040 and achieve a 40% emissions reduction target for 2030 compared to 1990 emissions, as stated in its nationally determined contributions (NDCs) under the Paris Agreement. Two main areas of focus will be switching to an emission-free transportation system and increasing carbon capture.

The Icelandic government announced a climate strategy in 2018 (Icelandic Ministry for the Environment and Natural Resources, 2018) and presented an updated Climate Action Plan with 15 new measures in June 2020 (Government of Iceland, 2020a). The new plan is based on several measurement improvements suggested by the Icelandic Climate Council and a report submitted by the Icelandic Environment Agency (Helgadóttir *et al.*, 2019). The plan is transparent on: the budget earmarked for most action items, the government entities responsible per task, the indicators to measure the success of each item, the expected emissions reductions potential of each measure, as well as the basis and sources of the corresponding estimations and forecasts.

As Iceland already enjoys virtually carbon-free electricity, the main sources of GHG emissions (not counting land use) are the use of fossil fuels for cars and ships, industrial processes and agriculture. Fisheries account for 18% of Iceland's directly attributable GHG emissions. Reducing emissions in this sector is one of the main priorities of the government (Government of Iceland, 2020a).

To demonstrate the government's ambition, all climate mitigation measures were promised a more than six-fold budget increase in June 2020. While in 2018, almost ISK 7 billion (EUR 43 million) were dedicated for the period 2019-23, in June 2020, ISK 46 billion (EUR 290 million) were announced until 2024 in an updated Climate Action Plan (Government of Iceland, 2020a).

A key component of the plan is to phase out fossil fuels in transport by 2030. Efforts in the maritime transport sector include planned electrification of ferries through green procurement, meeting electricity demands of all general ship operations in ports by 2025, and increasing the share of renewable energy and fuels for ships, especially fishing and government vessels (Icelandic Ministry for the Environment and Natural Resources, 2018). Energy transition of state-owned vessels was added to the Climate Action Plan in October 2020 (Government of Iceland, 2020b). By 2024, up to ISK 70 million (EUR 430 000) will be available to strengthen infrastructure for electricity and heat supply for ships in ports (Government of Iceland, 2020). As part of a Covid-19 pandemic fund, the government dedicated an additional ISK 300 million (EUR 1.9 million) to the energy transition, of which ISK 210 million (EUR 1.3 million) will go to electrification efforts in ports. The government formulated ten indicators in the latest climate plan to monitor achievement of the climate strategy for shipping and ports[16].

Norway

To date, Norway is the only Nordic country that has specified a separate emission target for the shipping sector. It has committed to halving emissions from domestic shipping and fisheries by 2030. Fjords will become zero-emission zones already by 2026 (Norwegian Maritime Authority, 2019). Any vessel entering a World Heritage Fjord in Norway will have to run on electricity or zero-carbon fuels.

More generally, it has pledged to reduce its overall GHG emissions by at least 40% by 2030 and at least 80-95% by 2050 compared to 1990 levels. This commitment was made as part of the country's nationally determined contributions (NDCs) under the Paris Agreement. The government announced that Norway will submit a more ambitious target for 2030 to the UN in 2020 (Government of Norway, 2018). The commitment and implementation of these objectives are reflected in Norway's Climate Change Act, which began on 1 January 2018 (Government of Norway, 2018).

In response to these binding targets, the Norwegian Government released the Action Plan for Green Shipping (Government of Norway, 2018) in June 2019. It outlines the technologies and solutions for reducing GHG emissions from shipping, the measures and instruments applied to different vessel categories, the role of infrastructure (ports) and the policy instruments to promote green shipping (Government of Norway, 2018).

Norway states three main international policy priorities (Government of Norway, 2018):

- become a driving force in efforts to strengthen the IMO's environmental protection rules
- adopt national policies to demonstrate possibilities and to develop low- and zero-emission technology with global potential
- provide aid funding to assist developing countries to make the necessary changes in their shipping sectors (NOK 10 billion – EUR 930 million – has been allocated for this purpose in the 2019 budget).

These targets are mirrored by the Norwegian private sector. The Norwegian Shipowners' Association (2020) has adopted a climate strategy, which consists of four objectives:

- by 2030, members will cut their greenhouse gas emissions per transported unit by 50% compared to the 2008 level
- from 2030, members will only order vessels with zero-emission technology
- from 2050, the Norwegian fleet will be climate neutral
- from 2050, members will promote an international ban on fuel types that are not climate-neutral.

Norwegian shipowners intend to achieve the first target mainly through efficient operation and retrofits to the existing fleet. The second target intends to provide clarity for the shipbuilding industry to target investments towards zero-emission solutions. The third target assumes that an absolute halving of emissions compared to 2008, as prescribed by the IMO, will require a 70-90% reduction in carbon intensity depending on the growth in shipping activity. This suggests that zero-emission technologies must be phased in as quickly as possible, and on a large scale from 2030. It also assumes the availability of low and zero-emission fuels at ports. Shipowners will need to adopt a proactive position to push the international regulator to ban non-climate-neutral fuels to meet the fourth target (Norwegian Shipowners' Association, 2020).

In 2018, the Port of Oslo adopted an action plan to become an emission-free port. The port's objective is to reduce GHG emissions by 85% by 2030 relative to the 2018 level. This covers emissions from port operations and from ships entering and leaving the port (Government of Norway, 2018).

Thirteen cruise ports in Norway have recently agreed on a common approach, with 14 joint measures to reduce emissions. For example, it requires cruise ships to use onshore power in all Norwegian cruise destinations with effect from 2025 and all ships entering and leaving port to operate emission-free, as soon as this becomes technically feasible (Larsen, 2020). The government aims for Norwegian ports to be emission-free by 2030, wherever feasible (Government of Norway, 2018).

Sweden

Sweden has committed to zero net GHG emissions by 2045 at the latest. This will require a GHG reduction of at least 85% in 2045 compared to 1990 levels. After 2045 Sweden must achieve negative net emissions.

The target for domestic transport, with the exception of domestic flights, is a GHG reduction by at least 70% by 2030, compared to 2010, as well as to contribute to the goal of climate neutrality by 2045 (Swedish Environmental Protection Agency, 2019).

Sweden adopted a new climate policy framework in 2017. The framework consists of the Swedish Climate Act and the Climate Policy Council. The Climate Act (Sveriges Riksdag, 2017) establishes that the government must:

- present a climate report in its Budget Bill each year
- develop a climate policy action plan every four years to describe how the climate targets are to be achieved
- ensure coherence between climate policy goals and budget policy goals.

The Climate Policy Council is an interdisciplinary expert body tasked to provide independent yearly assessments of the compatibility of overall policy and the national climate targets. These assessments require thorough emission reporting and monitoring. However, the Swedish National Road and Transport Research Institute (VTI) suggests that there are shortcomings related to the documentation of the official statistics, for example regarding transparency of applied methods. This currently makes it difficult to determine the factors to explain that some emissions increase or decrease from year to year (Vierth, Trosvik and Holmgren, 2020).

The Swedish Shipowners' Association, together with Fossil-free Sweden, has published a roadmap for a fossil-free maritime industry by 2045 in line with the Swedish law passed in 2017. The industry's strategy includes an "Action list for fossil-free and competitive shipping", which lists technical, financial, operational and organisational measures to be undertaken by the shipping industry to reduce GHG emissions (Fossil-free Sweden, 2019). These measures are neither binding nor bound to any specific agreement or timeline. Among others, the industry aims to secure longer chartering contracts to create certainty for financing greener vessels, harmonise industry eco-labels and indices, train staff, market low-carbon shipping with customers and to establish port-ship interface optimisation measures, etc. The contributing organisations also put forward a list of recommendations for authorities, municipalities and other public actors, including financial, technical, organisational and legal measures (Fossil-free Sweden, 2019).

Ports and terminals in Sweden have started to pronounce individual targets. The Port of Gothenburg (2019) for example announced that port-related carbon emissions will be reduced by 70% by 2030 throughout the whole of the Gothenburg area.

Research and innovation policies for maritime transport

Developing research activities and demonstration projects are timely and costly ventures for companies in the maritime industry. They often require massive initial investment that leads to negative cash flow for a long time. The necessary safety and risk analysis in order to obtain an approval in accordance with IMO guidelines for alternative design or alternative fuels (IMO 1456) can also be burdensome and costly. Thus, the push to achieve zero-carbon shipping needs a proactive government approach that minimises risks for companies willing to adopt zero-emission technology, and that bridges research with real-life application.

Maritime policies in the Nordic region equally support environmental, innovation and industrial policies. They encourage basic and applied research for the technological innovation required to reach emission targets, and create jobs and increase economic value in the maritime sector by supporting frontrunners and successful clusters that can export their technology. In particular:

- Many research programmes have required participation by actors across the entire value chain. Triple-helix collaboration between government, industry and academia, has linked research with opportunities to apply low-emission solutions.

- Maritime cluster support and innovation partnerships initiated by Nordic governments and private stakeholders has helped to create a fertile environment for innovation and build professional networks.
- Additional marketing support and export finance helps to pave the way for future scale-up of low-emission technology.

Dedicated research programmes

There are a number of ongoing public and private research programmes in the Nordics. Norway has the highest level of support and diversity of publicly funded programmes. Though proactive government policies and established formal and informal industry networks have also backed maritime projects in Denmark and Sweden. Nordic countries have been able to build on existing institutions and research programmes that have helped comply with environmental legislation, such as air pollution control in the Northern and Baltic Sea SO_x Emission Control Areas (ECA).

A number of schemes involving multiple actors test for a full project cycle to ensure that prototypes and trials do not stop halfway towards real-life application. This covers the research and the demonstration phase to market introduction and investment finance for customers wishing to apply the new solution.

Denmark

The Danish government provides subsidies for the testing, development and demonstration of new environmental technology solutions (Danish Ministry of Environment and Food, 2017). One example is the Environmental Technological Development and Demonstration Programme (MUDP). The distinction of this programme is its board, composed of 50% private sector representatives. It has provided grants to a number of companies and research institutions carrying out projects in shipping. Many of them have been rooted in compliance with previously enacted IMO legislation, as most shipping projects have a focus on measuring or reducing air pollution and ballast water treatment (Danish Ministry of Environment and Food, 2019).

The MUDP supports private companies and universities developing renewable energy technologies, energy efficiency technologies, conversion technologies such as fuel cells and hydrogen, integration of energy systems and storage of CO_2 (EUDP, ELFORSK and Innovation Fund Denmark, 2018). The programme was created with the broader objective to commercialise new energy technology faster, to develop Denmark as an attractive hub for green innovation and to increase competitiveness of Danish green technology exports. However, Danish energy technology exports and services appear to have lost momentum between 2014-17. EUDP et al.'s (2018) report also indicates that overall public funding for energy research in Denmark has decreased between 2010-17.

The Danish Maritime Fund is a private foundation established in 2005. In 2019, the Fund allocated DKK 10 million to low- and zero-emission technology research (Danish Maritime Fund, 2020). It was established under the Danish Parliament's Act when the Danish Ship Credit Fund transformed into the public limited company Danmarks Skibskredit AS. The Danish Maritime Fund has 10% of the share capital in Danmarks Skibskredit, the return on which constitutes the Fund's primary income.

The Innovation Fund Denmark is responsible for the implementation of the FORSK2025 catalogue of the Ministry for Higher Education and Science. Some of the key funding areas are energy efficiency and reduction of particles emissions (Danish Ministry of Industry, Business and Financial Affairs, 2018). The Fund also supports SMEs and entrepreneurs via the InnoBooster and InnoFounder programmes.

The A.P. Moller Foundation announced the creation of the Centre for Zero Carbon Shipping, in June 2020 (Maersk, 2020). This non-profit R&D centre aims to pool a number of partners under a co-operative framework to drive the transformation towards decarbonising shipping. Partners include the American Bureau of Shipping, A.P. Moller Maersk, Cargill, MAN Energy Solutions, NYK Line and Siemens.

Finland

Support from the Finnish government for research programmes focuses principally on digitalisation and autonomous shipping. Business Finland is the public organisation for innovation funding. It was previously Tekes, the Finnish Funding Agency for Technology and Innovation, which was fused together with Finpro Oy, the Finnish export promotion agency, in 2018.

The Arctic Seas Programme (2014-17) with an overall budget of EUR 100 million supported a number of energy efficiency projects in shipping, including the use of Flettner rotors on a Norsepower vessel (Business Finland, 2017).

Iceland

Iceland does not currently have a dedicated research programme for innovation in maritime transport. Emission reduction in the maritime sector is focused on fisheries.

Norway

In Norway, Enova, Innovation Norway, the Research Council of Norway and the NO_x Fund support the development of new technology and the required infrastructure (Government of Norway, 2018).

Enova is a public funding agency owned by the Ministry of Climate and Environment. It supports investments in climate and energy projects in all sectors. About one-third of Enova's budget is used for transport projects. Maritime activities account for the largest share of Enova's transport budget. Since 2015, Enova has allocated NOK 1.5 billion (EUR 200 million) to projects involving vessels fitted with batteries or charging facilities for low- or zero-emission vessels. Over the same period, Enova provided around NOK 500 million (EUR 46 million) towards the development of shore power in Norwegian ports. In 2019, the Green Fund for Climate, Renewable Energy and Energy Efficiency Measures increased its funding to Enova by NOK 485 million (EUR 45 million) (Government of Norway, 2018).

Innovation Norway is a funding agency focused on sustainable industrial restructuring and innovation. Maritime projects have been their second largest area of funding, with an estimated NOK 73 million (EUR 6.8 million) donated in 2017. Grants include those to help invest in: charging and mooring systems for electric ferries, smart charging, heating and energy management systems, and systems for hydrogen bunkering. Innovation Norway's contract scheme helps SMEs implement technologies together with pilot customers. Maritime SMEs have received around NOK 25 million (EUR 2.3 million) per year under this scheme. In addition, Innovation Norway initiated a NOK 30 million (EUR 2.8 million) grant scheme for pilot and demonstration projects in the marine and maritime sectors in 2018 (Government of Norway, 2018).

In 2018, the Norwegian Catapult Programme established three national centres for testing and simulation of new technologies, including solutions for decarbonising the maritime sector. The centres aim to help companies (mainly SMEs) to accelerate the process from concept to market introduction. The Ocean Innovation Norwegian Catapult Centre (OINC) in Bergen focuses on green restructuring of ocean industries. The Sustainable Energy Catapult Centre on Stord is a test facility for maritime and decentralised energy systems (batteries, fuel cells and hybrid systems). The focus of the DigitCat Catapult Centre in Ålesund is simulation, digital twins and virtual prototyping (Norsk Katapult, 2020).

The NO_x Fund, further discussed in the following section, reallocates the fees paid by shipping companies on NO_x emissions. Companies can make payments to the Fund per unit of their NO_x emissions instead of paying the tax on NO_x emissions introduced in 2007. In addition to reduction of air pollution, government estimations show that projects supported by the Fund have also achieved lower annual CO_2 emissions in the order of 400 000 tonnes CO_2 (Government of Norway, 2018).

The Research Council of Norway runs the Innovation Programme for Maritime Activities and Offshore Operations (MAROFF). One of the priority areas is greening maritime transport. This includes energy efficient vessels, deploying alternative energy carriers, reducing air pollution, research on framework conditions, such as tendering and licensing terms, and, incentives, such as quotas, fees and deductions. An important objective of the programme is also to ensure knowledge transfer between the R&D community and the maritime industry. In 2017, the Ministry of Trade, Industry and Fisheries allocated NOK 169.3 million (EUR 15.8 million) to the MAROFF programme, which was subsequently increased by another NOK 25 million (EUR 2.3 million) in 2018. In addition, the research council obtained a further NOK 17 million (EUR 1.6 million) earmarked for maritime technology development and maritime innovation (Government of Norway, 2018).

The PILOT-E scheme is a funding scheme launched by the Norwegian Research Council, Innovation Norway and Enova and is directed at consortia in the energy and transport sectors. The scheme covers research to full-scale demonstration and a plan for market introduction. Customers planning to apply a newly developed solution may qualify for investment aid from Enova. Overall, maritime projects received grants totalling NOK 107 million (EUR 10 million). Three out of six projects involved hydrogen solutions[17]. The last call for projects in 2019 was targeted at a zero-emission hydrogen value chain. A project led by BKK, Equinor and Air Liquide was selected and awarded a grant of NOK 33.5 million (EUR 3 million) (NCE Maritime CleanTech, 2018a). The 2020 call focuses on projects for zero-emission maritime transport. Available funding was increased in connection with the Covid-19 crisis (Enova, 2020b).

The PILOT-T scheme is a collaboration between the Research Council and Innovation Norway at the interface between digitalisation, safety/security and emissions reduction. The Research Council provides up to NOK 40 million (EUR 3.7 million) to projects in the research stage. Innovation Norway made up to NOK 25 million (EUR 2.3 million) of funding available for development and demonstration projects (Government of Norway, 2018; Research Council of Norway, 2019).

In 2015, the Centre for Research-based Innovation (SFI) established Smart Maritime, a “centre for improved energy efficiency and reduced harmful emissions from the maritime sector” (Smart Maritime, 2020). The centre’s objective is to green maritime transport by supporting feasibility studies and projects addressing hull and propeller optimisation, power systems and fuel, and ship system integration.

In addition to publicly led research initiatives, Norway also has a number of private research programmes. The most prominent example is SINTEF, a private, independent research institute with a department dedicated to maritime transport. For example, SINTEF Ocean develops solutions for energy production and energy use on ships. This includes new technologies for energy production, simulations and modelling, operational profile studies and the use of alternative fuels (SINTEF, 2020b). The institute has also been involved in the development of hybrid power systems, including the integration of batteries and fuel cells together with diesel generators (SINTEF, 2020a).

Sweden

The Swedish Transport Administration (Trafikverket) is the main funder of maritime research in Sweden. In April 2019, the government decided to increase the budget committed to maritime research to SEK 100 million (EUR 10 million) per year from the previous SEK 55 million (EUR 5.5 million) per year until 2022. The maritime programme has four priority areas, one of which is climate and environment. The programme has funded technical development, as well as research on policy measures (Trafikverket, 2020).

The Swedish Energy Agency's maritime research programme was created in March 2018 and allocated SEK 83 million (EUR 8 million) from July 2018 to December 2023. The program has issued two calls for projects nearing SEK 15 million (EUR 1.5 million) aimed at research and development projects with an innovation being a main focus for all areas of the programme: vessels' energy efficiency, conversion to renewable energy use and operational and systems adaptation (Swedish Energy Agency, 2020a). A call for projects in August 2020 announced approximately SEK 25 million in additional funding for the same programme (Swedish Energy Agency, 2020c). As part of the Swedish Biofuels Programme (2017-23), SEK 45 million was announced in March for the improvement of processes for biofuels for road transport, shipping and aviation (Swedish Energy Agency, 2020b).

The Swedish Innovation Agency VINNOVA has funded projects that combine research, technological development and demonstration projects, including projects such as EffShip (from 2009-2013), which aimed to address NO_x and SO_x emissions from shipping (EffShip, 2009). The project involved the Gothenburg shipping cluster, with 11 partners from industry, academia and local public authorities.

Maritime innovation partnerships and clusters

In the Nordics, research efforts supported at government level are often accompanied by industry partnerships and cluster initiatives that provide a fertile environment for innovation. In clusters, the co-location of actors allows for quicker and easier interaction and knowledge spill over. Strong linkages between large companies and local SMEs, as well as academic institutions and authorities, can generate important opportunities for local maritime employment, strengthening knowledge and mobility of personnel within the sector. In addition, strong clusters benefit from self-reinforcing upgrading mechanisms, as firms face nearby competition and pressure for innovation, complementary resources and need to access specialised knowledge (Benito et al., 2003).

There are two approaches for maritime cluster organisation:

- government-initiated partnerships or clusters that tend to fund their activities partly with government budgets (top-down) and
- cluster organisations driven by leader firms and/or sector associations (bottom-up).

While top-down clusters have the advantage that they can positively influence broader common interests, such as environmental concerns, bottom-up clusters generally tend to perform better in identifying concrete business opportunities and solving short-term issues, due to closer and organically formed interaction (Viederyte, 2013). Nordic countries have managed fairly well to strike this balance, with strong environmental leadership coming from both companies and government.

Denmark

An example of a successful proactive top-down approach is Blue Denmark. This is one of 13 partnerships that were initiated by the government to establish green business forums representing all sectors of Danish maritime industry. The partnership includes shipowners, shipping companies and other actors such as shipbrokers, shipyards, ports and logistics companies. A significant feature of this partnership is the co-operation and mutual consultation between government and industry actors when developing innovation policies and regulations.

Blue Denmark comprises a number of sub-partnerships and initiatives, such as Inno+, the Danish Maritime Days and Green Ship of the Future. It also intends to market innovative Danish maritime companies abroad and attract foreign maritime companies to the cluster in Denmark (Partnership for a Blue Denmark, 2020).

Green Ship of the Future (GSF) is an independent network for shipowners and operators, original equipment manufacturers and suppliers, classification societies, industry organisations and public authorities, and research and educational institutions. Currently, the group consists of 51 members (Green Ship of The Future, 2020).

A platform that applies triple-helix collaboration between government, industry and academia is ShippingLab, which ensures continuation of the Blue INNOship partnership to form a permanent maritime platform for research, development and innovation. The platform was initiated by Danish Maritime, Danish Shipping, Force Technology, Maritime Engineering DTU (Technical University of Denmark), CBS, Danish Metalworkers Union and the Danish Maritime Authority. The Danish Maritime Fund has committed funding work towards a project application for the Innovation Fund. ShippingLab projects (current to November 2020) include:

- Testing ISO8217 bio-bunker from waste products on boilers and engines (ShippingLab, 2020b).
- Developing fuel oil from whole biomass which is validated in the lab and producing quantities that will be sufficient for ship testing (ShippingLab, 2020a).
- Developing a hybrid dredging vessel for Hvide Sande Port. This includes the production of hydrogen from local wind power sources and use of surplus heating from the district heating network. The vessel will use a hybrid electric power solution with batteries and fuel cells, using compressed gas hydrogen. The design phase runs from 2020-21 and the demonstration phase from 2022-24 (ShippingLab, 2020c).

The Liaison Committee for Maritime Research establishes dialogue between business and maritime universities. It also develops specific project ideas that can serve as a basis for applications to public and private research councils and convenes annual discussion rounds on key maritime research topics (Danish Maritime Authority, 2020). The main areas of focus are: energy efficient technologies and systems, efficient operation and maintenance of ships, optimisation of transport chains and logistics, as well as health and safety.

The Maritime Research Alliance of Denmark consists of DTU (Technical University of Denmark), Copenhagen Business School, the University of Southern Denmark, Aalborg University and Copenhagen University, as well as professional institutions SIMAC and MARTEC. The Alliance began in 2018 and is a platform for cross-disciplinary research projects that address challenges related to digital and sustainable ocean economy and governance and aims to be an entry point for collaboration with industry, as well as international universities and organisations (Copenhagen Business School, 2018).

The Green Shipping Project, an international research partnership launched in 2017, is managed jointly by the Copenhagen Business School (CBS Maritime) and the Centre for Transportation Studies at the University of British Columbia in Vancouver. It includes 18 universities and 19 government, industry, and NGO partners. In September 2020, The Sustainable Shipping Initiative (SSI) and Copenhagen Business School (CBS Maritime) announced a new partnership under the Green Shipping Project. This collaboration aims to advance criteria that can establish sustainability credentials for alternative fuels and facilitate their certification. Subsequently, members plan to engage with certification bodies to facilitate the development of a sustainability standard or a certification scheme for marine fuels (SSI, 2020).

The Danish government actively supports the competitiveness of innovative maritime companies. In a 2018 document, the Danish government underlined that identifying markets for innovative maritime solutions should be a priority. The document “Maritime Denmark” presents a global maritime marketing strategy. It includes support for exports and easing potential financing and capital challenges through financing arrangements with neighbouring countries. The government also supports maritime SMEs in their internationalisation strategies, e.g. through digital information efforts and delegation visits to or from key export markets. The government plans to use governmentally- and municipally-owned ships for marketing purposes and to showcase technologies for export promotion. As major clients, public authorities should “continuously prioritise innovation, environment and climate solutions in public procurement”, for example by using innovation partnerships (Danish Ministry of Industry Business and Financial Affairs, 2018).

Last but not least, the Maersk Mc-Kinney Møller Centre for Zero Carbon Shipping, a non-profit commercial foundation, intends to identify decarbonisation pathways across the entire shipping sector. Working with industry, academia and authorities it aims to accelerate the development of selected decarbonising fuels and powering technologies and support the establishment of regulatory, financial and commercial means to enable transformation (Maersk, 2020).

Finland

In 2018, INTENS, a VTT-co-ordinated consortium of 19 actors from maritime research and industry, committed over EUR 13 million, including funding support of EUR 5.6 million from Business Finland. The focus of the funds is on improvements for digitalisation, energy efficiency and ship emissions reduction (VTT, 2020).

The Finnish maritime cluster encompasses about 3 000 companies and employs more than 50 000 people in Finland (Breaking Waves, 2019). The cluster organisation is a collaboration network organised by the Finnish Shipowners’ Association and the Finnish Port Operators’ Association (Finnish Maritime Cluster, 2020). It receives funding from the European Maritime and Fisheries Fund and Centre of Economic Development, Transport and the Environment.

Business Finland supports exporters in the shipping industry (Business Finland, 2019). Their comprehensive Shipping Manual contains import regulations for 190 countries and aims to support companies at different stages of the export.

Iceland

Iceland’s maritime clusters currently involve mainly the fisheries sector without any specific focus on innovation, energy efficiency or emissions reduction.

Norway

The Green Shipping Programme is the result of a public-private partnership initiated in 2015 to develop solutions GHG emissions from shipping and to strengthen Norway’s position as a global leader in the maritime sector. The programme emerged from previous collaboration between the classification society DNV GL, the Norwegian Ministry of Climate and Environment, and the Norwegian Ministry of Trade, Industry and Fisheries. The programme counts more than 60 partners from across the shipping community, including observers representing the public authorities. Programme partners launched some 20 large-scale pilot projects, including two sustainable port projects, the development of an LNG/VOC/battery-powered shuttle tanker, a hydrogen-powered speed boat, a bunkering vessel, and two autonomous, zero-emission vessels (DNV GL, 2017).

Norway has a rich tradition of maritime clusters, many of which have recently moved their focus towards clean shipping. The NCE Maritime Clean Tech cluster is a triple-helix collaboration platform specifically focused on the development of new energy-efficient and environmental friendly technologies. More than half of the cluster's members are innovative SMEs. Nine research organisations, universities and technology centres are also part of the cluster (European Cluster Collaboration Platform, 2020). The cluster organisation has established a number of sustainable innovation projects with commercial potential, including electric, hydrogen and green ammonia test vessels (NCE Maritime CleanTech, 2018b). At the same time, projects have addressed future fuel infrastructure needs, including a project building a green liquid hydrogen value chain (funded by the government's PILOT-E scheme) and developing onshore power supply.

With support from Innovation Norway's Arena Programme, the association Hub for Ocean has recently established the Ocean Hyway Cluster, which specifically targets hydrogen solutions. It brings companies in the maritime and energy sectors together with technology suppliers (Arena Ocean Hyway Cluster, 2020).

Local industry clusters exist, for instance, in Møre. The Blue Maritime Cluster assembles maritime companies, and specialised research and educational institutions. By assigning the Blue Maritime Cluster the status of 'Global Centre of Expertise', the Norwegian Ministry for Trade and Industry assists the cluster's strategic collaborative projects (Blue Maritime Cluster, 2020).

Sweden

The Swedish Maritime Competence Centre "Lighthouse" is a platform for collaboration and knowledge sharing on research and innovation for the maritime sector (Lighthouse, 2020). It is based on triple-helix collaboration involving the shipping industry, marine technology companies, academia and institutes as well as the public sector through the Swedish Maritime Administration and the region of Västra Götaland.

Five of its ten priority areas are related to greening shipping (Lighthouse, 2015):

- evaluation and reduction of shipping's negative effects on the climate, environment and public health
- alternative energy for ship propulsion and energy supply
- energy efficiency within the maritime sector
- financial incentives to support transition to sustainability within the maritime industry
- innovative shipping concepts and naval architecture and Integrated transport systems and business models.

Lighthouse established an industry programme called Sustainable Shipping that runs over ten years (2019-2028) and is carried out on behalf of the Swedish Transport Administration. The objectives are: at least 20 pre-studies, five completed research projects and eight completed innovation projects in the following areas:

- ship design, propulsion and operation
- maritime employment and skills
- efficient transport systems, instruments and business models
- digitalisation and automation.

Lighthouse is an active member of Waterborne Technology Platform, which is the EU's technology platform for shipping and marine technology (SEA Europe, 2020). Lighthouse also aims to develop a common national agenda for maritime research and innovation.

Pricing and incentives for maritime transport decarbonisation

Pricing and price incentives are essential elements of the policy toolbox to reduce shipping emissions. This can take the form of putting a price on CO_2 emissions (carbon pricing), financial incentives (such as subsidies and tax exemptions for green behaviour), environmental pricing of maritime services and green procurement.

Carbon pricing

The Nordic countries have been frontrunners in carbon pricing since their introduction of carbon taxes starting in the 1990s. Finland introduced its carbon tax in 1990, Norway and Sweden in 1991, Denmark in 1992 and Iceland in 2010. The nominal CO_2 tax rate ranges from around EUR 23 per tonne of CO_2 in Denmark to around EUR 110 per tonne in Sweden (Table 6). Norway, Sweden, Finland and Denmark also participate in the European Union emission trading system (EU-ETS). Energy use that is subject to the EU-ETS is generally exempt from the CO_2 tax or benefits from a reduced carbon tax rates.

Table 6. Overall carbon taxes in Nordic countries

Country	CO_2 tax rate per tonne CO_2	CO_2 tax rate (EUR)	Shipping included?
Denmark	DKK 173	23	No
Iceland	ISK 4235	27	No
Finland	EUR 62	62	No
Norway	NOK 500	46	Yes
Sweden	SEK 1150	110	No

Source: OECD (2019a); World Bank (2018)

The effect of carbon prices on CO_2 emissions is so far mixed. Various earlier empirical studies on carbon taxes in the Nordic countries found that carbon taxes had very small to no effects on CO_2 emissions (Bohlin 1998; Bruvoll and Larsen 2004), the only exception being the carbon tax in Finland where a significant and negative impact on the growth of its per capita CO_2 emissions was observed (Lin and Li, 2011). However, a recent study on Sweden – applying a different methodology – found a significant causal effect of a carbon tax on emissions (Anderson, 2019).

The carbon tax applies to domestic shipping in Norway, but not in Denmark, Sweden and Finland. In Norway, the carbon tax rates for inland transport depend on the energy source, with highest rates for petrol and lowest rates for heavy mineral oils, such as ship fuels. In 2006, the average carbon tax for inland transport and domestic shipping was NOK 190 (EUR 17.6) per tonne CO_2, compared to NOK 208 (EUR 19.3) per CO_2 tonne for taxi operations and domestic air transport (Bruvoll and Dalen, 2009). Since 2018, Norway applies the standard carbon tax rate also to LNG and liquefied petroleum gas (LPG) for domestic shipping.

International shipping is excluded from all emission trading schemes in the world, but domestic shipping is included in some. A notable example is the case of Shanghai. This is one of the Chinese regional pilots on emission trading schemes, introduced in 2013. In the scheme of Shanghai both ports and domestic shipping are included. This means that firms such as Shanghai International Port Group get assigned a certain amount of GHG emission rights that cannot be exceeded, unless they buy additional rights from firms that manage to reduce their GHG emissions. The leakage effect could be considered to be small considering the inevitable position of Shanghai when it comes to port activity (Shanghai has the world's largest port) and domestic shipping (ITF, 2018b).

The European Commission plans to include shipping in the EU-ETS, as part of the EU Green Deal package that includes the ambition to accelerate GHG emission reductions from shipping. In September 2020, the European Parliament supported the inclusion of CO_2 emissions from the maritime sector in the EU Emissions Trading System (ETS) using revenues to support investment in innovative technologies and infrastructure, such as alternative fuel and green ports, to decarbonise the maritime transport sector.

Similar pricing mechanisms: the NO_x Fund

One of the most referenced examples of pricing of shipping emissions is Norway's NO_x Fund. The idea is that instead of paying the NO_x tax, firms that operate ships in Norwegian waters can pay a NO_x fee related to the NO_x emissions of the ship. These revenues can fund innovative projects aimed at reducing NO_x emissions from ships. Companies that join the NO_x Agreement are entitled to an exemption from the tax of NOK 22.69 (EUR 2.1) per kg NO_x to the state from the date that the enterprise affiliates with the NO_x Agreement. The rates of payment to the NO_x Fund in 2020 are NOK 16.5 (EUR 1.5) per kg NO_x for the offshore industry (oil and gas extraction) and NOK 10.5 (EUR 1) per kg for the other sectors, including shipping, fishing, land-based industry, aviation and district heating. The affiliated companies need to report their emissions to the NO_x Fund based on a defined methodology. An accredited firm or approved competent party needs to carry out the measurement of the emissions. Classification society DNV GL will assure the quality of the information before the NO_x Fund will be able to provide support.

From 2008-19, the NO_x Fund supported approximately 1 330 projects that were reducing NO_x emissions: donating over NOK 4.4 billion (EUR 410 million). . Of this amount, around NOK 1.2 billion (EUR 110 million) was used to stimulate LNG-powered ships. Among the 134 shipping projects supported between March 2018 and May 2020, 34% were for projects related to shore power, 29% for selective catalytic reduction (SCR), 25% for batteries, 13% for LNG and 8% for energy efficiency[18]. In 2020 the NO_x Fund withdrew its support for shore power and energy storage on ships. This was because the Norwegian agency Enova established a separate programme for these emission reduction measures that the NO_x Fund considers already adequate in most cases. If companies can document rejection from Enova, the NO_x Fund might consider continuing their support.

According to the NO_x Fund, its contributions resulted in cumulative reductions of over 39 000 tonnes of NO_x and 1 million tonnes (Mt) of CO_2, and to significant development and dispersion of environmental technologies, for example LNG-powered ships. Not only domestic shipowners and operators can apply for this financial support, but also foreign owners that operate their ships in Norwegian waters. For example, various Swedish shipowners indicated that approximately 80% of the additional costs of LNG ships related to equipment were covered by the NO_x Fund (ITF 2018a). As such, the NO_x Fund creates knowledge spillovers that exceed national boundaries.

In 2017, the European Parliament proposed that a European Maritime Climate Fund be formed, based on the outcomes of the Norwegian NO_x Fund. In 2020, the European Parliament voted for integration of the shipping sector in the EU-ETS to be designed along similar lines (European Parliament, 2020). At the same time, there have been various proposals to establish a CO_2 fund at the national level. In Sweden, the Swedish Energy Agency (2017) proposed to develop a CO_2 Fund for shipping, which could help to upscale innovative solutions to decarbonise maritime transport, but which has not received the support needed for implementation. Pinchasik and Hovi (2017) proposed a CO_2 fund for the Norwegian transport sector and the Norwegian Airline Industry association has called for a CO_2 fund specifically for aviation. Heimvik

(2020) argued that such refunded emission payments (REP) schemes have qualities that could make it appealing to regulators, especially if an effective emission tax is unfeasible.

Subsidies and tax exemptions

Nordic counties – like many OECD countries – provide subsidies and tax exemptions to the shipping sector. These provide important levers for governments to stimulate decarbonisation of the shipping sector. Tax exemptions for current ship fuel act as barriers to change, whereas electricity tax exemptions could help the uptake of electrification of ships. Other instruments that could be the greening of tonnage taxes, tax reductions for research and development and subsidies for modal shifts and greening of shipping.

Ship fuel tax exemptions

Ship fuel is frequently exempt from or not subject to taxation. Countries generally do not levy excise duties on ship fuel for international maritime transport. Conversely, these are common taxes on road transport fuels. The resulting absence of taxation of ship fuels does not facilitate GHG emission reductions from shipping. Some countries would report these as tax expenditures, but not all countries do. Not relying on fuel taxes or related carbon pricing instruments will increase the cost of transitioning to cleaner technologies.

Countries generally do not impose ship fuel taxes unilaterally, because of the potential for tax competition, tax avoidance and carbon leakage. However, these effects are limited for domestic and regional shipping, which explains why fuel taxes exist for domestic shipping in various countries. For example, in Canada the federal excise tax applies to domestic navigation, and in Colombia both excise and carbon tax apply to domestic navigation. In some countries, sub-national governments have introduced ship fuel taxes. For example, the state of California taxes ship fuel purchased in California that is consumed in California and at first out-of-state destinations (up to the next non-Californian port).

All Nordic countries, with the exception of Iceland, provide fuel tax exemptions for the shipping sector. These take the form of energy tax exemptions for domestic shipping fuel in Sweden and Finland, exemptions from the CO_2 tax in Norway and Sweden, and the energy duty exemption for ferries in Denmark. Together, these fossil fuel subsidies (via energy tax exemptions) amount to EUR 174 million per year (Table 7). This overview does not include the fuel tax exemptions for international shipping by Nordic shipping companies, or the international shipping in Nordic territorial waters.

Table 7. Shipping-related fossil fuel subsidies

Country	Measure	Budget (million local currency)	Budget (million EUR)
Denmark	Energy duty exemption for ferries	DKK 196	26
Finland	Energy tax exemption for domestic shipping	EUR 3	3
Norway	CO_2 tax exemption gas and LPG used in shipping	NOK 120	11
Norway	Exemption on basic tax on mineral oil	NOK 780	73
Norway	Acceleration depreciation petroleum operations	NOK 65	6
Sweden	Energy tax exemption for domestic shipping	SEK 330	31
Sweden	CO_2 Exemption for domestic shipping	SEK 250	24

Source: OECD (2019a).

Electricity tax exemptions

Sweden, Norway and Denmark apply reduced electricity tax rates for shore power and electric charging of ships. This reduced rate can provide an incentive for commercial shipping to use onshore power and electric means of propulsion. The reduced rate is determined by the minimum level of taxation set out in the EU Energy Taxation Directive and allowed temporarily by the European Commission at request. The Swedish Energy Agency recommended in a 2020 report to extend the tax reduction for land-based electricity in ports to smaller vessels – less than 400 gross tonnes – that are currently not covered by the reduced rate (Swedish Energy Agency, 2020a). The monetary value of the lower electricity tax for shore power to ships represented DKK 15 million in tax expenditures in 2017 in Denmark (OECD, 2019b) and SEK 8 million (EUR 780 million) in Sweden in 2020 (EC, 2020).

Table 8. Reduced electricity rates for shipping in Denmark, Norway and Sweden

Country	Regular rate (per MWh)	Reduced rate for shipping (per MWh)	Reduced rate for shipping (EUR)
Denmark		DKK 400	EUR 54
Norway	NOK 1613	NOK 505	EUR 47
Sweden	SEK 185-293	SEK 50	EUR 6

Source: OECD (2019a).

Greening tonnage taxes

A tonnage tax is a specific tax for the shipping sector that replaces a regular corporate income tax. The tax base is the net tonnage of the ships that a shipping company operates (hence the name of the tax), rather than corporate income or profit. The tonnage tax is favourable to the shipping sector as it results in lower tax burdens than those incurred by a regular corporate income tax. As such, it has become one of the main mechanisms to subsidise the maritime sector in recent decades. While Greece has had a tonnage tax since 1957, many European countries started to introduce a tonnage tax after the Netherlands put one in place in 1996. Currently, more than twenty EU countries have introduced a tonnage tax and certain non-EU countries have done so as well, e.g. Japan, South Korea and India. Norway has had a tonnage tax since 1996, Denmark since 2002 and Finland since 2003, whereas Sweden only introduced its tonnage tax scheme in 2017 (ITF, 2019b).

The tonnage tax schemes of some countries differentiate according to the environmental performance of ships. In Norway, a shipping company can obtain up to 25% of a reduction of the standard tonnage tax, dependent on the environmental rating of their ships. This incentive, introduced in 2000, aims to reward companies for exceeding the mandatory requirements of the environmental performance of their ships. Companies may submit a voluntary declaration to the Norwegian Maritime Authority. The authority originally applied three categories of environmental criteria used for determining the environmental rating of a ship: air emissions, operational discharges from the ship into the sea, and the prevention of accidental discharge into the sea. In 2014, the Norwegian authorities adjusted these criteria by adding CO_2 emissions, sewage and garbage handling, and the implementation of an environmental accounting system for ships. They also updated the existing air emissions criterion, considering the more stringent IMO regulations for NO_x and sulphur emissions. The utilisation of the environmental incentives was modest: in 2012 the estimated revenues foregone were NOK 0.3 million and NOK 0.4 million in 2013, which is less than 1% in total tonnage tax revenues that otherwise would have been accrued to the Norwegian state (EFTA, 2014).

There are only a few other countries in the world, in addition to Norway, that have introduced environmental incentives in their tonnage tax scheme. In Portugal, a reduction of up to 20% of the amount of the tax base could be granted to vessels with a tonnage of more than 50 000 net tonnes that use mechanisms for the preservation of the marine environment and climate change mitigation. Other tonnage tax schemes provide incentives for younger vessels, which could facilitate GHG emission reductions if new vessels are more energy efficient than existing ones. E.g. the tonnage tax scheme in Malta provides a reduction from the standard tonnage tax rate where the vessel is less than ten-years old, and increases the tonnage tax payable when then vessel is fifteen years old or more (ITF, 2019b).

In 2007, Norway offered an environment fund as part of transitional measures within the context of the tonnage tax. These measures were put in place to transition from a shipping tax regime that postponed taxation of operational profits, until otherwise distributed to shareholders, to a system in which taxation of profits is tax exempt on a permanent basis. The idea was that up to one-third of the deferred tax – from the previous system – could be set aside to an environmental fund and used for environmental investments. The original measure envisaged that the environmental investments must take place within a period of 15 years from 2017, but Norwegian authorities abolished this time limit in 2009 and then the environmental fund altogether in 2010, as the tax charges under the 2007 transitional rules had been repaid (EFTA, 2009, 2010).

Despite its green outlook, the Norwegian tonnage tax actually enables the fossil fuel industry. Support vessels in petroleum activities are eligible for the Norwegian tonnage tax – and thus for exemption of the regular corporate income tax – as long as their activity constitutes maritime transport as such, or maritime transport by analogy. Vessels included by analogy means vessels that perform activities that share a sufficient number of characteristics comparable with maritime transport, e.g. that the vessels operate in a market open to international competition, the vessels require qualified seafarers and there is a risk for de-flagging and relocation (EFTA, 2017b).

Tax reductions for research and development

Government tax incentives also support the research and development that maritime shipping firms undertake. In Norway, the SkatteFUNN tax incentive scheme provides tax deductions for business expenses of research and development. In 2017, companies in the maritime sector received tax deductions totalling NOK 480 million (EUR 45 million) under the scheme. Small- and medium-sized enterprises can claim 20% of project costs as tax deductions, and larger firms can claim 18%. The scheme is rights-based and has a statutory basis, and applies to all branches of industry and all companies, regardless of size (Norway Ministry for Climate and the Environment, 2019).

Subsidies for modal shifts

Norway and Sweden have subsidy schemes to support transport modal shift of freight from road to water. Introduced in 2017 in Norway and in 2019 in Sweden, the schemes have many things in common. Both schemes grant direct aid to shipowners to develop new coastal or short sea services, if they avoid truck traffic and generate environmental and wider social benefits. Authorities can grant this aid based on a detailed business plan demonstrating the modal shift with quantifiable environmental benefits. The difference in marginal external costs of freight transport by sea and road transport forms the basis of the aid. Notably, the subsidy sum per service consists of the multiplication of the tonne-kilometres shifted from road to water with the difference in external costs between road and sea transport.

The Norwegian scheme distinguishes four levels of urbanity classification, with different external costs for road transport. The higher a level is urban, the higher the external costs of road freight transport. As a result, external benefits of the modal shifts range from NOK 0.187 (EUR 0.017) to NOK 1.974 (EUR 0.18) per tonne-kilometre. The Swedish scheme is simpler and provides one number for the difference between external costs from road and water freight transport (SEK 0.12 – EUR 0.012 – per tonne-kilometre). These assumptions are summarised in Table 9. The comparison shows that the Norwegian schemes has assumptions on the external benefits of modal shift that are considerably higher than those in the Swedish scheme, more than ten-times higher for modal shifts in highly congested urban areas with more than 100 000 inhabitants.

Table 9. Subsidies for modal shift in Norway and Sweden

Country	Measure	Period	Overall budget (mn)
Norway	Aid scheme Short Sea Shipping	2017-22	NOK 382
Sweden	Eco-bonus scheme	2019-20	SEK 150

Source: EFTA (2016, 2017a); EC (2018).

Table 10. Assumptions on external costs (EUR) per tonne-kilometre in modal shift subsidies in Norway and Sweden

Country	External costs maritime transport	External costs road freight transport	External benefits of modal shift
Norway	0.00094	0.018-0.19	0.018-0.18
Sweden	0.0048	0.016	0.012

Note: The following exchange rates have been used for this comparison: NOK 1 = EUR 0.094, SEK 1 = EUR 0.096.

Source: EFTA (2016, 2017a), EC (2018).

The Norwegian scheme aims to achieve an annual transfer of 100-300 million tonne-kilometres from road to waterborne transport, for the duration of the scheme (EFTA, 2016). The Swedish scheme does not quantify its targets. Both grant schemes cover up to 30% of the operational costs of the service and are expected to lead to commercial viability of the service after a maximum of three years of subsidies. Payments of the subsidies are made on a regular basis, upon evidence of traffic moved. In exceptional circumstances, the aid scheme can support existing services, if clear evidence is provided that the services in question would disappear in the absence of financial support by the state (Norway), or if it provides upgrades to existing services (in Sweden only for this last point).

Some countries outside of the Nordic region have also introduced subsidies to promote modal shift to short sea shipping. Italy granted an aid scheme, also called Eco-Bonus, between 2007 and 2011, with a total budget of over EUR 60 million. The design of the subsidy was different from Norway and Sweden: instead of providing direct aid to shipowners, the Italian scheme granted subsidies to road haulage companies that make use of existing or new maritime routes over road transport. Applicant companies had to carry out at least 80 journeys a year on an individual route, and received an additional bonus if they conducted more than 1 600 journeys a year with a given shipping line.

Subsidies for greening shipping

Many subsidies for green shipping in the Nordic region over the last decade have focused on SO_x and NO_x emissions. Some of the examples include:

The NO_x-RED scheme introduced in 2007 by Norway is not to be confused with the NO_x Fund. The objective of the NO_x-RED scheme is to decrease NO_x emissions from existing marine engines and newly installed marine engines of vessels in the Norwegian Shipping Register. Costs that are eligible for subsidisation consist of the investment costs necessary to achieve higher emission reductions than the ship would achieve in absence of the aid: the NO_x-RED scheme supports investments that go beyond those required by the MARPOL Annex VI regulation. The grant may be up to 30% of the eligible costs in case of engine modification and 15% in the case of replacements. Investments carried out by SMEs may get an increase of 10%.

Finland's investment aid scheme supports improvements in the environmental performance of vessels. Although the objectives of the scheme were broad, the direct motivation was provided by the designation of the Baltic Sea as an Emission Control Area (ECA) and EU sulphur directives (European Commission, 2011). The eligible costs for the scheme are defined as the extra investment costs necessary to reach a higher level of environmental protection than the level required by European Union standards on sulphur emissions from vessels. These costs constitute the extra investments that are eligible for subsidisation and are verified by the VTT Technical Research Centre of Finland or a similar research institute (European Commission, 2011). Part of the scheme was used to facilitate the Viking Line acquisition of a LNG-powered ferry, operating a regular route between Turku (Finland) and Stockholm (Sweden). The grant covered part of the eligible costs – the difference in the investment needed for an environmentally friendly solution and the reference solution – amounted to EUR 28 million. The support, granted in 2012, contributed to the first-ever large passenger ship powered by LNG. At the time of the investment, no LNG bunkering facilities were in place in the ports of Turku and Stockholm, safety rules for LNG powered ships were not yet finalised by the IMO and safety rules for LNG bunkering were not yet developed (European Commission, 2012).

In Norway, the maritime transport climate-related items that receive most of the funding are batteries, electrification and shore power projects in ports. These are funded by the agency Enova, whose allocations over 2017-19 were NOK 10.4 billion (EUR 97 million), of which NOK 2.7 billion (EUR 250 million) for the transport sector. At the end of 2019, Enova had supported battery installation and other energy efficiency measures in about 75 vessels with more than NOK 500 million (EUR 46 million), in addition to a small number of fully electric vessels. In terms of funding commitments, Enova has awarded more than NOK 900 million (EUR 83 million) for the electrification of 39 ferry connections with 52 associated ferries. Between 2015 and 2019, it supported 89 onshore power projects in more than 60 Norwegian ports with more than NOK 600 million (EUR 55 million) (Enova, 2020b). In Sweden, the main areas of the maritime programme of the Energy Agency are energy-efficient vessels, adaptation to renewable energy and operational efficiency. This maritime programme of the Swedish Energy Agency will allocate SEK 83 million (EUR 8.1 million) in funding between July 2018 and December 2023 (Energimundigheten, 2020).

Table 11. Subsidies for greening shipping in Norway and Finland

Country	Measure	Period	Overall budget (mn)
Norway	NO_x-RED scheme	2005-2009	NOK 60 (EUR 5.6)
Finland	Investment aid to greener vessels	2012-2014	EUR 120
Norway	ENOVA subsidies for maritime transport	2015-2019	NOK 1200 (EUR 110)

Source: EFTA (2005, 2007); European Commission (2018); Enova (2020b).

Other government support

Specialised government-owned shipping banks enable governments to finance shipping in line with mandated strategies for climate change mitigation and other environmental needs. An example of such a policy is the application of Responsible Ship Recycling Standards in shipping loans by the German KfW IPEX Bank. Sweden has a state-owned shipping bank, Skeppshypothek, which could support decarbonisation of the shipping sector, if the state would revise its mandate to make it focus on financing initiatives aimed at zero-carbon shipping (ITF, 2018a).

Environmental pricing of maritime services

Environmentally differentiated port dues

Ports in the Nordic region were frontrunners in greening port fees. Various shipping firms and shippers in Sweden developed the Clean Shipping Index (CSI) to serve as a basis on which to apply port fee reductions. Most of the large ports in the Nordic regions have introduced some sort of green port fee system, in which ships with the best environmental performance get a reduction of port dues. This is usually based on the Environmental Ship Index (ESI), the Clean Shipping Index (CSI) and in some cases, the use of LNG as ship fuel. The impact of most of these schemes is marginal, as the difference for best and worst performing ships is too small: most schemes only provide a positive incentive for a few vessels and no negative incentive for the badly performing ships (ITF, 2018c). This critique also applies to some of the green port fee schemes in the Nordic region providing environmental discounts for port fees. The maximum environmental discounts in the main Nordic ports range from 5% in Stockholm and 6% in Helsinki to 20% in Gothenburg and 40% in Oslo[19].

Truly environmentally differentiated port fees are relatively new and for the moment restricted to cruise ships calling Norwegian ports. This practice is based on an index developed by Norwegian ports, called the Environmental Port Index (EPI). Unlike previously existing indexes such as ESI and CSI, the EPI measures the actual operational efficiency of a ship in a port (Box 2). Moreover, various Norwegian ports have developed a pricing structure that allows for a wide spread between the best and worst performing ships. E.g. in the ports of Bergen and Stavanger, the best performing ships get a 17.5% rebate and the worst performing ships a 150% surcharge on the general port tariff. Other ports apply smaller spreads; e.g. a maximum discount of 20% and surcharge of 12.5% in the port of Kristiansand[20].

Box 2. Environmental Port Index

The Environmental Port Index (EPI) was initiate by three Norwegian ports (Bergen, Trondheim and Stavanger), DNV GL and numerous shipping industry experts in 2019. The index provides a calculation for the environmental impact of ship operations, which are reported to shipowners and port operators, so that they may increase their operational efficiency while reducing their impact on the environment. Sixteen ports in Norway currently use the EPI. The initiators have the ambition to roll out the programme in other countries as well. For the moment, 111 cruise ships owned by 18 different shipowners have registered their technical configurations in the EPI database.

The EPI establishes a ship's maximum tolerable environmental impact while at port, based on major influencing factors including CO_2, SO_2, NO_x and particle levels. This is known as the ship's EPI Baseline. Upon departure from port, a ship's crewmember will sign into the secure EPI Portal. Here they will record the vessel's key utility data, such as fuel consumption, emission levels, and power usage during the ship's time at port. The data submitted via the EPI Portal is then compared to the ship's EPI Baseline. Once again, the EPI calculation comes into play and an EPI Score between 0 and 100 is calculated. Ships are awarded higher scores for beating their EPI Baseline and lower scores for falling short.

For each ship's stay at port, EPI Reports are generated in two main forms: the Port Operator Report and the Ship Owner Report. The Port Operator Report provides port operators with the EPI Score of each ship. This makes it easy to recognise which ships are operating more efficiently than projected while at port. The Port Operator Report also includes cumulative year-to-date data for all of a port's ship visits. This insight allows port operators to identify challenging areas and develop ways to support shipowners in reducing port pollution. The Ship Owner Report provides shipowners with a full report of their ship's performance while at port. This includes their EPI Score, but also a detailed breakdown of their data.

Shipowners can then see which areas offer opportunities for greater efficiency and potential associated benefits.

Source: Bergen Havn (2020).

Environmentally differentiated fairway dues

Sweden is one of the few countries with environmentally differentiated fairway dues. These are the tariffs to be paid by ships for accessing the fairway channels leading towards ports. This means that cleaner ships pay lower fairway dues, and less clean ships pay higher fairway dues. This system of environmentally differentiated fees has been operational since 1998. Although evaluations of its environmental impacts show mixed results, the system is unique in that all ships are covered by the polluter-pays principle. Fairway dues in other Nordic countries often apply environmental discounts. One example is that ships registered with the Environmental Ship Index (ESI) using the fairways near the port of Bergen are granted a discount on fairway dues of 20% if their ESI is above 30 points and a discount of 50% if their ESI is above 50 points.[21]

The Swedish fairway due system changed in three ways in 2018. First, it introduced a broader set of environmental indicators than the previous version based on NO_x emissions. The new fairway dues follow the scores of the Clean Shipping Index that takes not only NO_x emissions into account, but also SO_x, PM and CO_2 emissions, the management of chemicals on board, and waste management.[22] A second change was the introduction of new elements in the charging, namely a passenger fee and a "preparedness fee". Thirdly, the reform increases the cost recovery rate: a higher amount of the costs for the fairway system is now covered by fairway dues (ITF 2018a).

Public procurement

Various countries globally provide public service contracts: shipping services to remote islands, for example. These contracts rarely take carbon emissions into account, despite the huge potential they could have to capture this (Rehmatulla et al. 2017). The Nordic region provides some notable exceptions. For example, the public procurement for the maritime connection between Stockholm and Gotland incorporated GHG emissions; this, in combination with the ten-year duration of the contract, facilitated the order of LNG-propelled vessels by Rederi Gotland AB who won that contract and will decrease CO_2 emissions by 20%. Yet, there are also public procurement procedures that do not take decarbonisation into account. The city of Stockholm is in charge of several intra-urban ferry services for which GHG emissions do not seem to be considered a priority (ITF, 2018a).

A parliamentary bill from 2017 in Norway suggested that low- or zero-emission solutions for maritime passenger transport services should be a requirement in public procurement processes whenever possible. Although green public procurement might be picking up for local ferries and passenger vessels, an overview of public tender competitions in Norway indicated that there is still considerable potential for improvement by including environmental criteria (Bjerkan et al. 2019). The rapid transition to electric ferries in Norway was due to an urgent need for new- builds, facilitated by a public procurement setup favouring energy-efficient operations, i.e. hybrid or fully battery electric ferries.

Moving towards zero-carbon shipping

Nordic countries have high ambitions to reduce greenhouse gas (GHG) emissions from shipping. The policies they have developed to achieve these goals can inspire other countries and be scaled-up to regional and global intervention levels. The transition towards the uptake of low-carbon technologies is – like most transitions – determined by the interplay of local, regional and global initiatives and dynamics. These need to be considered when reflecting on how zero-carbon shipping could be achieved. Where global interventions could be essential for the Nordic region to realise a quantum leap towards zero-carbon shipping, Nordic interventions in turn could help shape circumstances necessary for such global interventions. The following section will address this interdependence by sketching possible options to move forward on zero-carbon shipping via improvements in energy efficiency, uptake of renewable energies and carbon pricing.

Energy efficiency

The technology analysis developed in this report shows that improving the energy efficiency of both new and existing ships is essential – yet still not sufficient – to meet international climate commitments. Efficiency improvements can be unlocked using readily available technologies, often with manageable payback periods making them cost effective. In addition to reducing the emissions intensity of ships, energy efficiency can help to limit additional costs associated with future low-carbon fuel options.

Over the last years, international regulation has been introduced to improve the energy efficiency of ships. Since 2013, all new ships have to be built in accordance with an Energy Efficiency Design Index (EEDI). The EEDI reference level is tightened every five years to improve energy efficiency of ships over time. Even if the impact of the EEDI on shipping's GHG emissions has so far been limited (UMAS, 2016), the EEDI is a well-established instrument that could be used to further improve energy efficiency. In addition to the more technically focussed EEDI, another IMO instrument provides guidance on *operational* efficiency of ships, both new and existing ships. This instrument is called Ship Energy Efficiency Management Plan (SEEMP), which contains guidelines for improving operational efficiency and a monitoring tool, the Energy Efficiency Operational Indicator (EEOI) that helps operators to measure the fuel efficiency of ships in operation and the impacts of changes in operation.

Progress in decarbonisation of shipping in the short term could be made by sustained focus on energy efficiency. The Initial IMO Strategy for Reduction of GHG Emissions from Ships (Initial IMO Strategy) lists various candidate measures that could be developed before 2023 – most of which covers the area of energy efficiency of ships. In order to elaborate such measures, IMO member countries have engaged in discussions since 2018, but this has not resulted in any concrete measures yet. In 2020, the decision is likely to be adopted to advance the start date of phase 3 of EEDI from 2025 to 2022 for certain ship types. Discussions have also started on a possible future phase 4 of EEDI that could imply a further tightening of the EEDI. One proposal that received considerable support, but not sufficiently large enough to result in agreement at IMO was a mandatory speed limit.

In 2019, the IMO's Intersessional Working Group on the Reduction of GHG emissions (ISWG-GHG) agreed to further discussions on technical and operational approaches, to be developed in parallel. Nordic countries have been pro-active in developing both these approaches:

The main proposal related to technical efficiency is to apply mandatory efficiency improvements in the existing fleet, known as EEXI (Energy Efficiency Existing Ship Index) similar to the EEDI for new ships. This was proposed by Japan and Norway in 2019 (ISW-GHG 6/2/3), and further developed in an informal workgroup with various other member countries, including Finland. The draft instruments developed include draft guidelines to calculate, survey and certify the EEXI. Part of the proposal is the notion that energy efficiency of a ship can be improved by reducing the propulsion power of the engine, which can be achieved by a shaft/engine power limitation. In order for ships to be able to have enough propulsion power in emergency situations, the proposal foresees a mechanism that allows ships to reserve power at a level that satisfies the requirements for minimum propulsion power.

Denmark, France and Germany, took the lead on an energy efficiency proposal (ISWG-GHG 7/2/9). This can be described as a mandatory goal-based, short-term measure. It targets an individual carbon intensity reduction and is assigned to each ship and shipowners, operators and crews are free to choose the means to reach it. Possible technical and operational means mentioned in the proposal include speed optimisation, trim optimisation, energy optimisation and use of alternative fuels. The use of appropriate Carbon Intensity Indicators (CIIs) is proposed to determine compliance of a ship with a required carbon intensity reduction, to ensure that the 2030 carbon intensity target in the Initial IMO Strategy will be achieved. Enforcement will be based on the ship's International Energy Efficiency Certificate (IEEC) to be renewed every five years with an annual verification audit on achievement of the ship's annual target. Lloyds Register has suggested a possible way in which the proposal could be implemented (Lloyds Register, 2020).

Adoption of both proposals by the IMO would help to achieve the IMO 2030 carbon intensity reduction target of at least 40%, provided that a few conditions are met. The engine power limitations that form the core of the EEXI proposal are likely to deliver minimal reductions in GHG emissions unless they are very stringent, according to recent research (Rutherford et al., 2020). Such concerns over the abatement potential of the EEXI-proposal strengthen the argument for considering both proposals as complementary rather than substitutes. One of the concerns expressed on the carbon intensity indicators per ship is that they do not take into account the variables that are outside the control of the ship, such as adverse weather conditions. A possible solution could be to come up with more specific CIIs for different trades. Some countries – India, Liberia, Panama, Singapore and United Arab Emirates – have used the uncertain impacts of CIIs as argument to plead for a phased introduction of enforcement of CIIs, where sanctions for non-compliance would only be applied in the third phase (ISWG-GHG 7/2/16). It is hard to see how CIIs could be effective drivers in reducing carbon intensity in the short term if they cannot effectively be enforced; more detailed, trade-specific CIIs and continuous review of the impacts of CIIs could likely mitigate the concerns on uncertainty of CII impacts.

Low-carbon fuels

The technology assessment in this report indicates that low-carbon fuels, such as renewable energies, will be required to reach decarbonisation of maritime trade. A wide range of possible fuels was assessed with regards to their technical barriers, lifecycle emissions, their potential to scale and their associated costs.

National action has proven to be effective in this respect. Domestic shipping emissions represent around 30% of total global shipping GHG emissions (IMO, 2020a) and national initiatives can have a direct impact on reducing these emissions of domestic shipping. Many of these national initiatives can also act as drivers of more global developments. On an institutional level, the interaction between national and global interventions is expressed in the voluntary submission by IMO member countries of their National Action

Plans to the IMO, as undertaken by Norway in January 2020. The national-global interaction is also required for aligning regulation, support infrastructure and incentives to facilitate transitions.

An example of this interaction over the last decade is the uptake of vessels fuelled by liquefied natural gas (LNG). The Nordic region has shown a remarkable uptake in this respect thanks to a more or less simultaneous development of demand for LNG-fuelled ships (via Norway's NO_x Fund and pioneering shipowners), the development of the relevant safety standards (IGF Code), long-term charters for LNG-ships and the roll out of LNG bunkering facilities in various Nordic ports. A similar process would be necessary for the uptake of renewable energies and alternative fuels.

This process is well advanced in electric ships, where the Nordic region has shown very significant leadership. Policy instruments such as inclusion of environmental requirements in government procurement processes, subsidies for electrifying ships and charging systems in ports in Norway, tax reductions in Sweden and Denmark, along with technology and battery cost developments, have been instrumental for this success. In a wider context, the EU Alternative Fuels Infrastructure Directive 2014/94/EU regulation has likely contributed to a push for shore power connections in the EU ports, by requiring ports in the TEN-T core network to provide LNG facilities or onshore power supply. Ship-to-shore power standards have been established by the International Standardisation Organisation (ISO), the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE).

The leadership that the Nordic region has taken on demonstration projects and adopting new fuels means that it is well placed to serve as a proving ground for the shipping fuels of tomorrow. Further research and demonstration projects in the Nordic region, particularly on promising fuels such as ammonia and biofuels are important to tackle the technical challenges involved in the use of low-carbon marine fuels. The public sector's buying power related to maritime services could also be leveraged to stimulate demand for zero-carbon harbour ships, tugboats and icebreakers. In addition to overcoming technical barriers, demonstration projects can serve to accelerate the regulatory and safety legislation necessary to deploy new technologies at scale under the short timeframes required to tackle climate change. With its large forestry sector, the Nordic region has a competitive advantage with respect to other global areas to ensure that biofuels contribute in a significant manner to its shipping fuel mix.

Regulation and standards are needed for approval and development of low-carbon energy carriers like biofuels, hydrogen and ammonia, the use of powertrains, batteries/storage tanks on board the vessels, as well as land-based energy infrastructure. Regulatory instruments like blending mandates and/or standards on the carbon content of fuels (on a well-to-wheel accounting basis) are likely to be instrumental to ensure that low-carbon fuels can be a sizable part of the shipping fuel mix. Nordic stakeholders would benefit from supporting the adoption of a life cycle (well-to-tank) framework when assessing energy use and GHG emissions of shipping fuels, supported by additional sustainability criteria, especially in the case of biomass-based fuels. This would promote energy efficiency, avoid the use of unsustainable biofuels and the production of ammonia or hydrogen with fossil fuels without carbon capture and storage.

Regulatory developments on the sustainability of fuel production are also necessary to avoid the undesirable impacts that fossil fuel substitutes can have on land use and land use change. The Nordic region is exposed to similar work developed in the context of the International Civil Aviation Organisation. As part of the European Economic Area and/or members of the European Union, Nordic countries have also contributed to develop the provisions related with sustainability requirements included in the Renewable Energy and the Fuel Quality Directives of the European Union. Nordic countries are therefore well positioned to encourage the use of similar frameworks in the IMO context. To ensure that these pre-requisites are effectively delivering on decarbonisation while leveraging on the competitive advantage offered by their established forestry sector, Nordic countries could take the lead in the adoption of national or co-ordinated regional regulatory requirements on low-carbon fuel blending and/or requirements for low-carbon content in fuels.

Batteries are a crucial component of electric ships, an area where Nordic countries are global leaders. Concerns about the sustainability of battery supply chains also apply to batteries used in ships and the materials needed for their production. Despite the fact that emissions from ship operations are likely to exceed significantly those imputable to battery manufacturing, due to long lifetimes and opportunities to use second life automotive batteries in ships, as in the case of stationary storage, taking a life cycle approach is also important for electric ships to ensure net GHG emission reductions overall. Work aiming to promote both sustainable and low-carbon battery manufacturing and end-of-life treatment has already started in the European Union, with an initial focus on automotive batteries. The continued engagement of Nordic countries in this work will also be instrumental to ensure that sustainability requirements for batteries are brought forward in the IMO.

Carbon pricing

Putting a price on carbon provides incentives to cut carbon emissions. It does so by increasing the economic viability of energy efficiency solutions and by opening up opportunities for switches to low-carbon fuels. Nordic countries have already shown significant leadership as frontrunners in the introduction of carbon taxes, environmentally differentiated port pricing and electricity tax exemptions for shore power connections. These initiatives could serve as inspiration for other countries that want to stimulate zero-carbon shipping. At the same time, there are still various financial incentive schemes that would need to be aligned to a zero-carbon strategy.

All Nordic countries also provide considerable state aid to the maritime sector, but only part of this aid targets the environmental performance of the shipping sector. In some cases, maritime state aid is actually a fossil fuel subsidy: shipping benefits from large-scale tax exemptions for ship fuel and the shipping-specific tonnage tax also applies to the shipping activities of the petroleum sector. Pricing mechanisms such as the NO_x Fund can help to reduce emissions from shipping and could potentially be developed into a CO_2 of GHG Fund for shipping.

Carbon pricing of shipping in national schemes is not sufficient; regional or global schemes are also required in order to stimulate the deployment of zero-carbon fuels. The 2018 Initial IMO Strategy mentions the development of new/innovative emission reduction mechanisms, possibly including market-based measures (MBMs), to incentivise GHG emission reduction. This prudent formulation reflects the challenge in the 2010s, despite years of discussion, to agree on a market-based mechanism, the jargon used to denote carbon pricing within the IMO community. Some countries, including the United Kingdom and various Pacific Islands, have recently made submissions to IMO requesting that market-based mechanisms be considered.

In the European Union, the European Parliament recently supported the inclusion of CO_2 emissions from ships of 5 000 gross tonnage in the EU Emissions Trading System (ETS), Europe's market based carbon pricing mechanism for the electricity and industry sectors. This requires the approval (and/.or negotiated amendments) of EU member states to become binding legislation. The decision of European MEPs followed the consideration that the IMO has made insufficient progress on the subject. It was accompanied by a call for the establishment of an "Ocean Fund", financed by revenues from auctioning allowances under the ETS to make ships more energy-efficient and to support investment in innovative fuel technologies and infrastructure and to protect, restore and efficiently managing marine ecosystems impacted by global warming (European Parliament, 2020).

Considering their experience with market-based mechanisms at the national level, Nordic countries could be well placed to bring this discussion forward at the IMO. This action could, in the first instance, take the form of a state of the art overview mapping possible proposals, based on policy practice over the last decade and taking into account the findings of the IMO expert group on market-based mechanisms that reported in 2010. In the second instance, a concrete proposal could be developed, taking into account potential effectiveness and political feasibility.

A proposal for a market-based mechanism could take the form of a carbon levy, an emissions trading scheme, a low-carbon fuel standard or a hybrid form, also including – as in the recent decision of the European Parliament – instruments allowing to fund the development of innovations.

Finally, regulations on the well-to-wake carbon intensity of shipping fuels and/or low-carbon fuel shares/quotas can also be instrumental to promote the adoption of low-carbon fuels for the maritime sector. These could complement carbon pricing or provide an alternative way to reduce GHG emissions from shipping fuels. Low-carbon fuel standards are an instrument to consider in this context, since they combine pricing, regulatory measures and the capacity to channel funds towards the best technology options at once, while remaining technology neutral.

Notes

1. Gross tonnage of a ship is a standard measure of its total internal volume. The deadweight tonnage is a measure of the maximum weight that a ship can carry.

2. Details depend on the size of the investment needed, the expected useful life of the ship, oil price assumptions and interest rates.

3. Split incentives can occur when the costs of investing in an abatement option are incurred by one party but the benefits accrue to another. In shipping, this takes place if a ship-owner, who would need to pay for an energy saving technology upgrade, does not have a return on its investment (e.g. in the form of a higher charter rate), for example because of the lack of proper information on the fuel consumption of a ship. Meanwhile, it is not commercially attractive for a charterer to take on financing if the payback of a technology is shorter than the duration of the charter (Fitzpatrick et al., 2019).

4. This assessment depends on the engine technology considered and the method used to account for the global warming potential of methane – higher in the first 20 years from the moment when the emissions take place than in following decades (Sharafian, Blomerus and Mérida, 2019; Pavlenko et al., 2020).

5. Cost-related challenges for biochemical pathways initially suggested a need to focus on higher-value markets for bio-based chemicals before targeting fuel production (IEA Bioenergy, 2014), but high interest in biojet fuel production spurred interest in the development certifications for biochemical fuels suitable for blending in jet kerosene (IEA Bioenergy, 2019). Addressing the cost challenges can also come from economies of scale. One example, also applicable to other pathways, is the idea to piggy-back onto existing biomass harvesting processes and alcohol (ethanol) production facilities, taking advantage of the existing supply chain for conventional production (IEA Bioenergy, 2014)

6. Some oils can be used as blend-ins without the added refining step. Maersk is currently investigating the blend-in potential of several renewable oils. This includes pyrolysis oils using end-of-life windmill wings and end-of-life car tyres. HTL from various organic materials also produces promising blend-in bio-oils. Sample quality has been good so far, and projects are underway. At-scale vessel pilots have not yet been performed but are planned (review input from Anne Sophie Vinther Hansen).

7. Syngas can also be converted to fuels that are gaseous at ambient temperature, in particular methane or di-methyl-ether (DME), with lower thermodynamic losses (but also disadvantages in the fuel distribution step).

8. An assessment carried out for the production of bio-gasoline using this process integration suggests that fuel yields per unit of carbon available in the biomass feedstock can be increased by over 2.5 times thanks to hydrogen enhancement. A biomass conversion process with hydrogen integration would require 25% more renewable energy than the energy contained in the fuel (Hannula, 2016a, 2016b). In contrast, synthetic fuels produced from the combination of hydrogen electrolysis and direct air capture (DAC) of atmospheric CO2 would require 150% more renewable electricity (than the energy contained in the fuel). See also (Albrecht et al., 2017).

9. Hydrogen production from electrolysis could be competitive with natural gas with carbon capture and storage with electricity production costs below 25 USD/MWh, a value that is already a reality for wind and solar electricity in highly endowed areas of the world, such as Morocco or Chile (IEA, 2019b; Armijo and Philibert, 2020).

10. This assumes USD 50/MWh for electricity and 3 000 full load hours for hydrogen electrolysers and it uses USD 400/t for CO2 from DAC (without specifying technical details on the DAC technology and its energy costs). In this case, electricity costs account for one-third of the total and CO2 costs for another third (See IEA, 2019b fig. 22).

11. Using marine diesel for auxiliary power demands in port produces approximately 700 g CO2/kWh of shaft power (Balcombe et al., 2019). The energy efficiency of electricity use from onshore power is approximately 0.75 (shaft kWh/grid kWh). Therefore, for onshore power to be a lower GHG intensity than diesel, electricity needs to be below 700 x 0.75 = 500 g CO2/kWh.

12. This figure aims to estimate the range of lifecycle emissions gCO2e per kWh of work at the propeller shaft (using GWP100). Ranges are calculated from past literature sources where available and estimated for other fuels. Values for LNG are sourced from (Pavlenko et al., 2020). Values for electric ships are calculated using the efficiency ranges presented in Figure 10 (76-80%) and a range of electric grid emissions intensities between 30-240 gCO2/kWh reflecting the current ranges in Norway and Denmark respectively. The higher the share of renewables in the electricity grid the lower the emissions intensity. This leads to use-phase emissions of 37.5316 gCO2/kWh at the propeller shaft. Embodied emissions associated with battery manufacture are then added to this, based on the analysis of (Kortsari et al., 2020) for the E Ferry. The E ferry batteries have 4 MWh capacity and are therefore assumed to have an associated 215-430 tCO2 from production (assuming 50-100 gCO2e/kWh battery capacity). The batteries are expected to last ~12 years after 24 500 cycles and 1 600 kWh flow per cycle. This equates to roughly 5-11 gCO2/kWh delivered.

13. Lifecycle emissions associated with gaseous hydrogen production are sourced from (Parkinson et al., 2019) as follows: H2 (renewable electrolysis) 0.47-2.5 kgCO2e/kgH2, H2 (SMR) 10.09-17.21 kgCO2e/kgH2, H2 (SMR+CCS) 2.97-9.16 kgCO2e/kgH2, H2 (CH4 pyrolysis) 4.2-9.14 kgCO2e/kgH2. Emissions for H2 (CH4 pyrolysis) could be lower than 4.2 kgCO2e/kgH2 provided renewable electricity were suitably integrated but this is not included here for lack of comparable peer reviewed research. The hydrogen production emissions of Parkinson et al., 2019) are then used to estimate ammonia production emissions via stoichiometry. Nitrogen air separation emissions are included for electrolysis and

methane pyrolysis production routes assuming 0.42 kWh/kg N2 (Bicer and Dincer, 2018) and electricity intensities of 30-240 gCO2/kWh. Ammonia production emissions are estimated as follows: NH3 (renewable electrolysis) 0.10-0.55 kg CO2e/kgNH3, NH3 (SMR) 1.78-3.04 kgCO2e/kgNH3, NH3 (SMR+CCS) 0.52-1.62 kgCO2e/kgNH3, NH3 (CH4 pyrolysis) 0.74-1.61 kgCO2e/kgNH3. Hydrogen and Ammonia production emissions are then converted into GHG emissions per kWh of propeller shaft work using the energy conversion efficiencies of Figure 10 for hydrogen and ammonia ships equipped with internal combustion engines respectively (40-50% hydrogen, 42-50% ammonia). All other fuels are sourced from the ranges presented by (Balcombe et al., 2019). Synthetic fuels are not included for a lack of comparable peer reviewed research. The resulting estimates shown are comparable to the magnitudes presented by (Lindstad, 2020).

14. This figure shows the energy conversions required to convert 100 kWh of renewable electricity into fuel and subsequently propulsion in a ship and takes inspiration from the work of (Cebon, 2020). Energy conversion efficiencies for electric ships are sourced from the evaluation report for the E Ferry (Kortsari et al., 2020). The energy efficiencies for water electrolysis are assumed to range between 60-70% (IEA, 2019b). Hydrogen cryogenic liquefaction entails losses of roughly 30% and is assumed 13.9 kWh/kgH2 (Lindstad, 2020). Hydrogen transportation losses due to boil off are assumed to range between 0% and 10%. The efficiency of a marine PEM Fuel cell is sourced from (Welaya et al., 2011). The efficiency of electric motors range between 90-95% (Balcombe et al., 2019; Cebon, 2020). The efficiency of hydrogen and ammonia internal combustion engines are assumed to be similar to those of conventional diesel engines and range between 42-50% (Wartsila, 2020). Ammonia is assumed not to suffer from significant boil off losses. The efficiency of ammonia use in a solid oxide fuel cell is estimated to be between 50-65% (Giddey et al., 2017).

15. Most of the largest Nordic ports provide LNG refuelling via ship-to-ship bunkering, whereas port-to-ship bunkering is often available in ports that have LNG terminals. This is particularly the case in Norway.

16. https://www.elysee.fr/admin/upload/default/0001/06/4b39ecc31afbb721391675c1316c03e0de739300.pdf (accessed 7 July 2020).

17. Annual use of fossil fuels in fisheries, use of fossil fuels per unit of power, number of ports where home fleet is connected, number of ports where service boats are connected to electricity, number of ports where cargo vessels can connect to electricity, number of ports where high voltage connection is available, percentage of black oil from total fuel consumption, number of cases of illegal use of black oil within Icelandic jurisdiction, the number and proportion of ferries in Iceland that run on green fuels, percentage of renewable energy of total energy of state vessels.

18. Selfa Arctic AS and Flying Foil AS are each heading a consortium 22 to develop solutions for high-speed vessels that improve energy efficiency and make it possible to use propulsion systems based on batteries or fuel cells. The Havyard Group ASA is heading a project to achieve emission free operations in the World Heritage Fjords and along parts of the coastal route Bergen–Kirkenes by combining batteries and hydrogen fuel cells. Samskip AS is leading a project to develop and realise profitable container transport by sea using hydrogen fuel cells for emission-free propulsion, making it possible to transfer goods from road to sea.

19. Some projects covered more than one category.

20. Based on data provided by port authorities on their websites: https://www.portsofstockholm.com/siteassets/prislistor/2020/sh-prices-and-terms-2020-version-2020-01-01.pdf
https://www.portofhelsinki.fi/sites/default/files/attachments/Price_List_2020_2.pdf
https://www.oslohavn.no/globalassets/oslo-havn/dokumenter/oslo-havn-planer-rapporter-brosjyrer-2019/port-of-oslo---port-tariffs-and-general-terms--conditions-2020.pdf
https://www.portofgothenburg.com/maritime/port-tariff/

21. Based on data provided by port authorities on their websites: https://www.stavangerhavn.no/wp-content/uploads/Pricelist-2020-1.pdf
https://bergenhavn.no/wp-content/uploads/2020/07/PRICELIST-2020_EN-002-1.pdf
https://www.portofkristiansand.no/en/tjenester/prisliste/

22. https://bergenhavn.no/wp-content/uploads/2020/07/PRICELIST-2020_EN-002-1.pdf

23. For more details on Clean Shipping Index: https://www.cleanshippingindex.com/methodology/

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Annex: List of workshop participants

Participant affiliation below was provided at the time the Workshop was held in February, 2020.

ALAMOUSH, Anas	World Maritime University
ALLGURÉN, Viktor	Port of Gothenburg
ANDERSSON, Charlott	Trafikverket
ANDRADE DOS SANTOS, Vinicius	University of Coimbra
ANKER SØRENSEN, Torben	Anker Invest
BALLINI, Fabio	World Maritime University
BERG, Thor André	Plug
BJARKAM, Jacob	PowerCon A/S
BURMAN, Åsa	Lighthouse
CAMARA, Bàkary L	World Maritime University
CAZZOLA, Pierpaolo	ITF
CHRISTODOULOU, Anastasia	World Maritime University
DALAKLIS, Dimitrios	World Maritime University
DANG CUONG, Nguyen	World Maritime university
DE VRIES, Rianne	GoodFuels
ENGSTRÖM, Rikard	Swedish Shipping Association
FOLORUNSHO, Abiodun	World Maritime University
FRIÐLEIFSSON, Sigurður Ingi	Energy Agency Iceland
GARY, Magnus	ShippingLab
GILA, Luvo	World Maritime University
GRÖNHULT, Jan-Olof	DNVGL Sweden AB
HANNISDAL, Karoline	Nordic Energy Research
HANSEN, Anne Sophie Vinther	Maersk
HENKE, Magnus	Swedish Energy Agency
HOENDERS, Roel	IMO
HOLM JØRGENSEN, Allan	PowerCon A/S
JEPPESEN, Michael	MAN Energy Systems
JOHANNESSEN, Tue	Maersk
JOHNSEN, Kevin	Nordic Energy Research
JÜRIADO, Rein	Swedish Transport Administration
KIRSTEIN, Lucie	ITF
KITADA, Momoko	World Maritime University
LAINIO, Ulla	Business Finland
LARSEN, Cecilie	Municipality of Ærø
LARSSON, Fredrik	Swedish Shipowners Association
LINDQVIST, Esa	Business Finland Oy
LYKKEGAARD, Cecilie	Danish Maritime

MARFE, Rejard	World Maritime University
MBOTIJI, Elizabeth	World Maritime University
MERK, Olaf	International Transport Forum
MKWAWA, Saidi	World Maritime University
MOENGEN, Trond	Energidata/Pilot-E
OFTEDAL, Sveinung	Ministry of Climate and Environment, NO
OKOKHUE, Happiness	World Maritime University
ÖLCER, Aykut	World Maritime University
ØYSTESE, Kirsten	Norwegian Climate Foundation
PÅLSSON, Christopher	Lloyd’s List Intelligence
PHILIBERT, Cédric	Self-employed
PORTIN, Kaj	Wärtsilä
PRYTZ, Anna	Forsea
QUESADA, Adriana	World Maritime University
RASMUSSEN, Jesper Dalsgaard	
RUIZ, Carlos	IRENA
RUJUB, Aziem	World Maritime University
SCHNELL, Kasper Alstrup	Danish Maritime Authority
SCHÖNBORN, Alessandro	World Maritime University
SCHRÖDER-HINRICHS, Jens-Uwe	World Maritime University
SINGER, Bryan	World Maritime University
SKIPPER SCHWENN, Maria	Danish Shipping
SKULASON, Jon Bjorn	Icelandic New Energy
SMITH, Tristan	UCL/UMAS
SØYLAND, Svend	Nordic Energy Research
SUN, Zhen	World Maritime University
TARNUE, Andrew Akoi	World Maritime University
TAUDAL POULSEN, Rene	Copenhagen Business School
VOLLA, Rune	Norges Forskningsråd
WIJAYANTO, Danuja	World Maritime University

Navigating Towards Cleaner Maritime Shipping

This report analyses future energy-use in the shipping sector of the Nordic region. It centres on pathways that could allow the Nordic shipping sector to meet energy and environmental policy goals, including energy diversification, cutting air pollution and reducing greenhouse gas emissions. It details the feasible technology options currently available, the status of their adoption and government plans aimed at influencing future developments in this sector. Finally, it assesses implications for policymaking for a rapid transition to cleaner maritime shipping. The Nordic region is pioneering efforts to reduce the environmental impact of maritime shipping, making the findings of this report relevant around the globe.

International Transport Forum
2 rue André Pascal
F-75775 Paris Cedex 16
+33 (0)1 73 31 25 00
contact@itf-oecd.org
www.itf-oecd.org

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