BLUE SUPPLY CHAINS

Role of Port Authorities in green energy supply for transports chains

The way towards a green bunkering and charging strategy for ports and emission free inland waterways connecting a seaport with the hinterland

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Green ports fostering zero-emissions in

BLUE SUPPLY CHAINS

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4S	4-stroke engine
2S	2-stroke engine
ASU	Air separation unit
bio-MEOH	Biomass based methanol
BoP	Balance of plant
CCS	Carbon capture and storage
CEPCI	Chemical Engineering Plant Cost Index
CH_2	Compressed hydrogen
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent, the standard measurement of GHG emissions in terms of the most common GHG, carbon dioxide (CO_2)
DME	Dimethyl ether
Elec-BE	Battery electric
e-LMG	Liquid Electro-methane
e-MEOH	Electro-methanol
e-NH_3	Electro-ammonia
ETS	Emission Trading System
GHG	Greenhouse gas
FC	Fuel cell
FCI	Fixed Capital Investment
FT	Fischer-Tropsch
HVO	Hydrotreated vegetable oil
H_2	Hydrogen
ICE	Internal combustion engine
IMO	International Maritime Organization, the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.
ISBL	Inside Battery Limit
LBG	Liquid Biogas
LCA	Life cycle assessment
LH_2	Liquefied hydrogen
LNG	Liquid Natural gas
MEA	Monoethanolamine

MeOH	Methanol
MEPC	Marine Environment Protection Committee
MGO	Marine gas oil
Net-zero GHG emissions	Removing an equal amount of CO_2 from the atmosphere as we release into it
N_2O	Nitrous oxides/ Dinitrogen oxide
NO_x	Nitrogen oxides
NG_{CCS}	Steam reforming of natural gas with carbon capture and storage
NH_3	Ammonia
OPS	Onshore Power Supply
OSBL	Outside Battery Limit
PEMFC	Proton-exchange membrane fuel cell
PM	Particulate matter
RME	Rapeseed methyl ester
RoPax	Roll-on/Roll-off and Passenger vessel in combination
RoRo	Roll-on/Roll-off vessel
SO_x	Sulfur oxides
SOFC	Solid oxide fuel cell
TFCI	Total fixed capital investment
Tank-to-Wake	TTW, used to describe the marine fuel’s combustion for transportation of goods and/or passengers (also referred to for land-based transport as tank-to-wheel).
Well-to-Wake	WTW, used to describe the marine fuel’s life cycle from the acquisition of the raw material to when the fuel is combusted for transportation of goods and/or passengers (also referred to for land-based transport as well-to-wheel).

Summary

What are required for ports to offer hydrogen-based fuels and electrical solutions to ships? What actors are involved that play a crucial role in the realization? Not all ports can be energy hubs, but ports that offer alternative fuels, onshore power supply and charging of batteries can have a strategic advantage in the future. This report includes the development of *emission-free inland waterways* and *a green bunkering and charging strategy* for ports. The focus is on the role of port authorities, but also other perspectives are important, as a shift from fossil fuels to low-carbon fuels requires collaboration among many actors. Therefore, the scope also involves the perspectives of shipping companies, port authorities, terminal operators, energy companies/producers, technology providers and authorities.

This report provides a comprehensive overview of alternative fuels and charging facilities for low-carbon shipping, and explores the development over time, including various aspects such as technical description and maturity level, national production capacity, infrastructure and storage needs, and environmental, economic and safety aspects. The report covers techno-economic assessment of renewable fuels such as methanol, hydrogen, and ammonia, including capital and operational costs, cost/benefit analysis, and sensitivity analysis. Furthermore, the report contains discussions about the national, EU, and IMO policies and funding programs related to sustainable shipping.

Almost all ships today still use conventional fuels of fossil origin. This is expected to change, but the uptake of renewable fuels will be slow the forthcoming years due to insufficient fuel production capacity, technical immaturity and slow implementation of regulation and requirements. Prerequisite for the shift is increased energy efficiency, because future low-carbon fuels will be more expensive and with limited production capacity initially. Renewable fuels to replace existing fossil fuels and measures to reduce the greenhouse gases of shipping included in this report are biofuels, methanol, hydrogen and ammonia, and battery electric and wind propulsion. Further, important driving forces and enablers for the development of low-carbon marine fuels and electric solutions are also highlighted.

This report gives directives to promote sustainable shipping, including *descriptions of* and *guidelines* for 1) *low-carbon shipping on inland waterways*, and 2) *a strategy for bunkering and charging of ships in ports for a specific country or region*. The *first part* addresses the Lithuanian Inland Waterway Authority's project of a fully electrified sea transportation system along Nemunas River between Kaunas to Klaipeda. The Guideline for low-carbon shipping on inland waterways represent a comprehensive framework aimed at reducing the carbon footprint associated with inland water transportation, with the objective to establish clear directives and best practices. The *second part* includes the development of a Swedish bunkering and charging strategy, with an assessment of present and potential future supply and demand of fuel production sites, bunkering and charging facilities based on annual port call statistics in all Swedish ports. The objective of the guideline for the national bunkering and charging strategy is to provide other countries around the Baltic Sea with a methodology to analyse supply and demand of energy in ports to serve the shipping industry, but also surrounding industries and terminal equipment, today and in the future. The purpose of these guidelines is to provide a roadmap for stakeholders in shipping to move towards low-carbon operations and contribute to the necessary reduction of ship and port emissions.

The following conclusions are highlighted:

1. No silver bullet – several fuels and solutions will be available in the future and complement each other.
2. Ships' emissions need to be greatly reduced – and it is urgent!
3. Likely development with a shift from centralised to more local production and bunkering, with synergies/competition between shipping and land-based industries.
4. Policies and regulations are required and essential for supporting development of renewable fuels and reducing ship emissions.
5. Pilot project and financial support is needed to prepare for full scale transformation.
6. Costs in all parts of the supply chain need to be reduced for renewable fuels to be competitive.
7. Cooperation among many actors is required and increased knowledge to grasp the quick development.
8. Business opportunities ahead!

1. Introduction

What are required for ports to offer hydrogen-based fuels and electrical solutions to ships? What actors are involved that play a crucial role in the realizations? This chapter introduce the background and the development of low-carbon marine bunker fuels and the driving forces behind the changes. Not all ports can be energy hubs, but some will and should. For those ports, offering of alternative fuels, onshore power supply and charging of batteries will give the port a strategic advantage.

1.1. Background development of new low-carbon fuels and electrification

For the shipping industry and ports to deliver on the long-term target of net zero carbon emissions, a transition from today's fossil fuels towards fossil-free alternatives needs to be introduced together with energy efficiency and other measures to reduce the need for marine fuels (Malmgren et al., 2023). The quantities of fuels consumed on-board ships as well as within and connected to ports are significant (Winnes & Styhre, 2017). Today, ships consume approximately 280 million tonnes of fuel annually, and more than 99% of the world fleet runs on fossil-based conventional fuel or LNG (DNV, 2023a).

This report takes a deep dive into the Swedish shipping and port sector as well as within a specific pilot project in Lithuania with a setup of a fully electric push barge system. In Sweden, some 30 TWh of fossil marine fuels are sold annually to domestic and international ships (Swedish Energy Agency, 2022), with fairly large variations in recent years, but with a steady rise since the 90s. In addition, terminals and ports also consume large quantities of diesel fuels (Winnes & Styhre, 2017). However, official statistics for international shipping are unreliable and the use of electricity in ports are missing (Vierth, 2023).

Interviews with ports and terminals (*Chapter 5.1 Stakeholders' view on present and future development*) show clearly that many port authorities are investigating the possibility to support the shipping companies that call their ports with the fuels they plan to use for their ships in the future. The ports need to do that on a commercial basis and understand financial and other risks, and make sure the investment will be long-term profitable. In addition, many ports and terminals have plans for their own operations to become net-zero carbon over time. Some ports also have targets for their customers' operations (shipping companies, freight forwarders, etc) to reduce their climate footprint.

At the time of this study (2023– spring 2024), some shipping companies ordering new ships have taken steps towards alternative marine fuels with lower carbon impact (DNV, 2023a). This development means that ships in the order books today include methanol-ready ships, possible to fuel with either MGO (marine gas oil) or methanol, and LNG (liquid natural gas) dual-fuel ships, possible to fuel with LNG, MGO, or LBG (liquified biogas). However, approximately 50% of the ships in the order books still plan to use conventional fossil fuels, see Figure 1. Further, an absolute majority of the existing ships are running on conventional fuels, and many have many years left in operation.

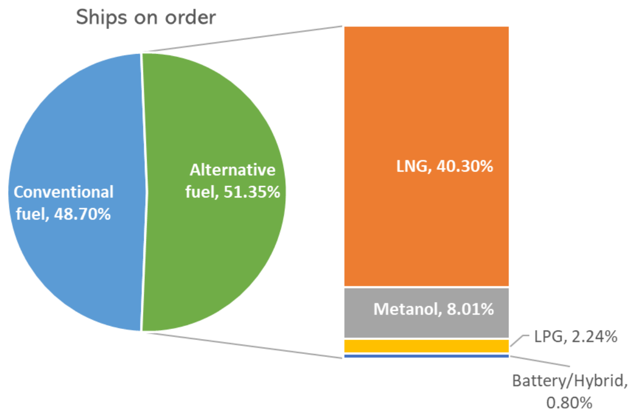


Figure 1. Alternative fuel in the ships on order books (Source: DNV, 2023a).

Ports and ships have operated shore-to-ship electricity (i.e. onshore power supply, OPS) for many years, and ports are also planning for new and further expansion of OPS connections to be built (Malmgren et al., 2023). However, the number of ships that use shore-to-ship electricity are still limited in Europe, and many ports and ships still lack necessary equipment. There is also an issue with lack of standard. Terminal tractors, cranes and other heavy vehicles and equipment are, in many terminals, already being operated on renewable HVO or electricity. There are also plans for pilot tests for hydrogen-powered heavy vehicles.

All in all, the development to be further analysed, and around which a strategy will be formed, has certainly already started. However, massive investments in the sector of decarbonising ports and ships are ahead of us.

1.2. Stakeholder landscape

There are many stakeholders of the shipping industry that affect the development to decarbonise transport and port operations. This chapter explores what roles and actors are needed in the future to support the emerging market for alternative fuels such as hybrid electric technologies, hydrogen technologies, and electrofuel technologies. The specification and description of actors is based on Malmgren et al. (2023), Latapí et al. (2023), Hansson et al. (2023) and previous project experiences.

1.2.1 Description of existing actors and roles in the shipping industry

The actors that play an important role in the shipping industry's low-carbon transition are divided into the port community, transport providers and brokers, cargo owners, technology and energy providers, authorities/regulatory authorities/decision makers, universities/research institutes and other notable groups of actors. In some cases, one actor can take many roles. For example, in Sweden, many ports are owned by the municipality and have combined port authority, port management, terminal operation and stevedoring within the same organisation. Further, many larger shipping companies have an internal department for transport bookings, while they also work with external cargo brokers and freight forwarders.

The port community

The port authority is responsible for overall port management, including infrastructure development, security, and regulatory compliance. They play a central role in coordinating activities and ensuring that the port operates in accordance with local and international regulations.

Port management involves overseeing the day-to-day operations of a port, including infrastructure maintenance, cargo handling, security, and coordination of various activities. Port managers collaborate with terminal operators, shipping companies, and other stakeholders to optimize port efficiency and ensure smooth operations.

Terminal operators manage specific port terminals where cargo is loaded, unloaded, and stored. They are responsible for optimizing terminal efficiency, handling cargo operations, and maintaining terminal equipment and infrastructure.

Stevedoring, including dockworkers, crane operators, and administrative staff, are responsible for loading, unloading and handling of cargo at a terminal. Labour unions represent the interests of these workers and negotiate employment conditions and agreements.

Shipping agents act on behalf of shipowners, charterers, or ship operators to handle various administrative tasks in ports. They assist with customs clearance, documentation, and communication between the ship and port authorities, ensuring a smooth ship call in port from an administrative point of view.

Transport providers and brokers

Shipping companies own or operate vessels transporting goods to and from ports. They negotiate contracts with freight forwarders and shippers, schedule vessel arrivals and departures, and play a key role in global supply chain logistics.

Cargo brokers/freight forwarders facilitate the arrangement of transportation for cargo owners and charterers. They connect cargo owners with available shipping capacity, negotiating terms and ensuring the smooth flow of goods.

Rail and road transport providers own or operate trains or trucks to and from ports. They negotiate contracts with freight forwarders and shipping companies and carry out the shippers' transport assignments.

Cargo owners

Shippers (e.g., cargo owners) are companies who own, or are responsible for, the goods being transported via the port. They play an important role because they can make demands on sustainability, service requirements and mode of transport when purchasing transport.

Charterers are individuals or companies that lease or charter a ship to transport goods. They may charter the entire vessel (full charter) or a portion of it (part charter) to meet their transportation needs.

Technology and energy providers

Technology providers, such as port management software, and other service providers contribute to the efficiency and innovation of port operations.

Energy suppliers, such as energy companies or fuel producers are companies or entities responsible for supplying fuel, typically marine fuel, or marine bunker fuel, to the port area. The fuel production is a value chain and could therefore consist of several firms developing projects, building production facilities and distributing the fuels.

Bunker companies, supplier of marine oil products in ports that use bunker ships, and pipelines or possible tank trucks for smaller quantities to fuel ships. Ships can take on bunker both at quay in port or at anchorage within or outside the port area. Mainly larger ports provide bunkering fuels for cargo ships.

Authorities/regulatory authorities/decision makers

Maritime commissions are governmental or quasi-governmental bodies responsible for regulating and overseeing maritime activities within a specific jurisdiction. They may be involved in formulating maritime policies, issuing licenses, and ensuring compliance with maritime laws and regulations.

Flag State Control refers to the regulatory authority of the country under whose flag a ship is registered. The flag state is responsible for enforcing international maritime regulations on its registered vessels, ensuring they adhere to safety, environmental, and labour standard.

The IMO is a specialised agency of the United Nations responsible for regulating shipping on a global scale. IMO establishes international standards for the safety, security, and environmental performance of international shipping. It also facilitates cooperation among member states to address maritime issues.

The EU shapes maritime policies, regulations, and funding programs in Europe that impact ports and maritime activities. Through directives, regulations, and initiatives, the EU establishes common standards for port operations, environmental protection, safety, and security across member states.

Local authorities, including municipal or regional governments, act within the governance and management of ports and maritime infrastructure at the local level. They may for example own and operate ports and oversee land-use planning and zoning regulations.

Universities/research institutes

Training institutions provide education, training, and professional development programs for individuals working in the maritime and port industry. They collaborate with industry stakeholders to ensure that training programs meet industry needs and standards.

Research and academic institutions conduct studies, research, and analysis on topics related to ports, maritime transportation, and logistics. They contribute to the development of innovative technologies, best practices, and policy recommendations to address challenges and opportunities in the maritime sector.

Other notable groups

Financial institutions, such as banks and investment firms, play a crucial role in funding ship programs, port infrastructure projects and maritime initiatives. They provide loans, grants, and investment capital.

Non-governmental organizations, such as environmental organizations, advocate for improved practices within the maritime sector. They may engage in policy advocacy and collaborate with industry stakeholders to promote initiatives.

Labor unions and workers' representatives advocate for the rights and interests of workers employed in ports, maritime transportation, and related industries.

Trade associations represent the interests of businesses operating within the maritime industry.

There are many interactions between the different actors, both for handling of the physical goods flows and information, as indicated in Figure 2. The shipping sector is intricated, and multiple actors exchange physical goods and information. In the energy transition, interactions with emerging energy and propulsion technologies will be important and will be discussed in the later sections of the report.

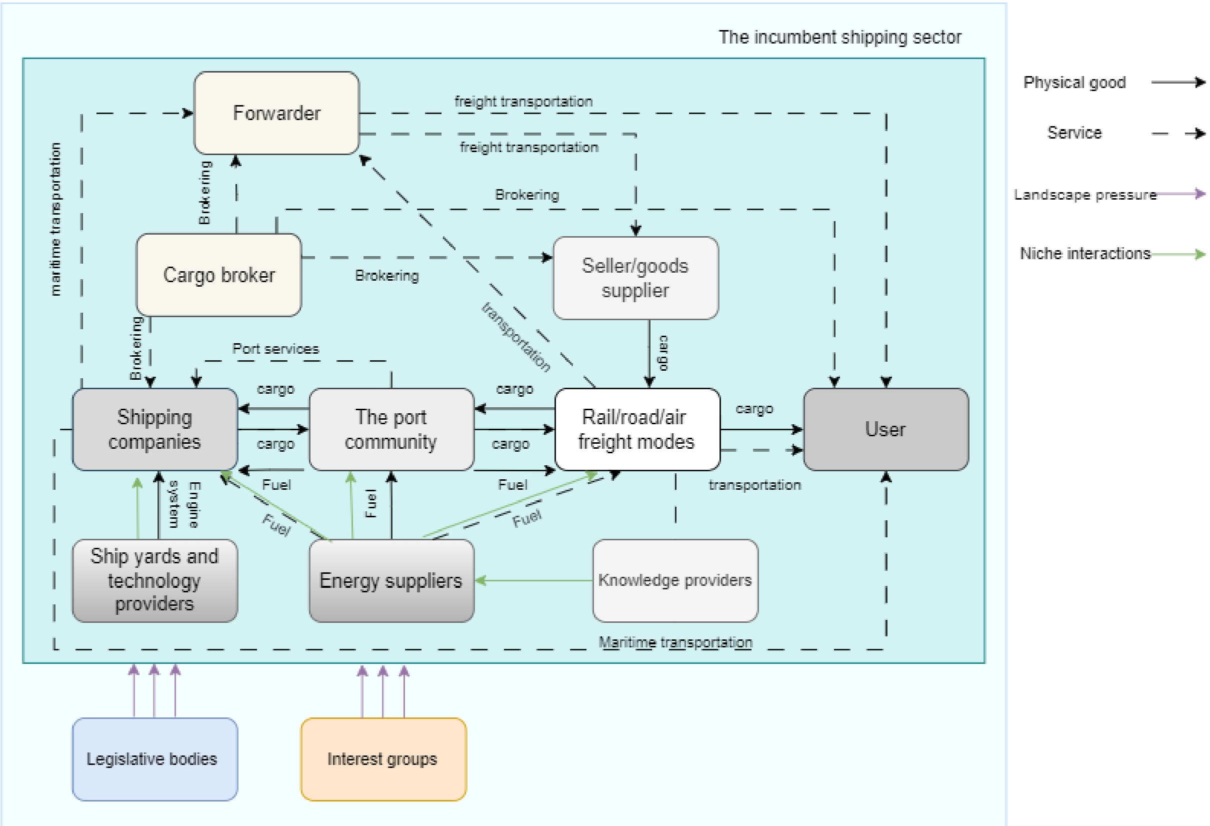


Figure 2. Mapping of the roles of the actors in the shipping industries and their interactions. The shipping sector is intricated, and multiple actors exchange physical goods and information.

1.2.2 The role of port authorities in the decarbonisation of the shipping industry

The future role of ports, as clusters of organisations and as physical nodes, is central to the decarbonization of the shipping sector and is thus explored by many scholars and industry actors. This chapter discusses the potential role of port authorities in the sustainability transition of the shipping industry, seen from a socio-technical systems change perspective (Geels, 2011) and how they could engage with both incumbent actors and emerging technologies.

A socio-technical system could be defined as “the linkages between elements necessary to fulfil societal functions (e.g., transport, communication, nutrition)” Geels (2004, p.900). Socio-technical systems “encompass production, diffusion and use of technology” (Geels 2004, p. 900). The concept combines the fields of evolutionary economics, science and technology studies (including innovation as a process of co-creation) and structuration theory (Geels, 2011). Damman and Steen (2021) argue that viewing the shipping industry as a socio-technical system is motivated because large sectors are subject to lock-ins and path dependence, where technological challenges are closely tied to user practices, business models and institutional practices. The port (as a physical and economic node) could be seen as such a lock-in, where large investments have already been made and institutional practices are developed. Shifting into low-carbon solutions requires change in the existing socio-technical system (Damman & Steen, 2021).

The socio-technical system could in turn be viewed from a multi-level perspective (Geels, 2011; Geels, 2004), which conceptualises the transition of systems through a three-levelled lens: the bottom level consisting of radical innovations (e.g., new technologies) developing in protected *niches*, the socio-technical *regime* level where established practices and rules that work to stabilize the system, and lastly, the *landscape* level consisting of exogenous factors and elements impacting the lower levels (Geels, 2011).

Viewed from a socio-technical system perspective, ports (comprised of the cluster of organisations with the roles of landlord, operator and regulator) are actors in a matured regime (the shipping industry) and are therefore incumbents (as opposed to emerging actors and markets) in the system (Damman & Steen, 2021. As such, they could have several roles to play in a sustainability transition, acting as either inhibitors or promoters of the transition by engaging with emerging technologies and changing the logics of the regime (Damman & Steen, 2021). Examples of emerging niches in shipping is hydrogen and battery electric technologies and companies developing these technologies could consist of incumbent energy companies as well as market entrants with innovative business models. Regime actors include not only port authorities, but also ship owners and other stakeholders in the existing system, described in 1.2.1. The landscape pressure could be exerted from legislative bodies like the IMO or EU, but also from social pressures created by changing demand from customers. This is illustrated in Figure 3.

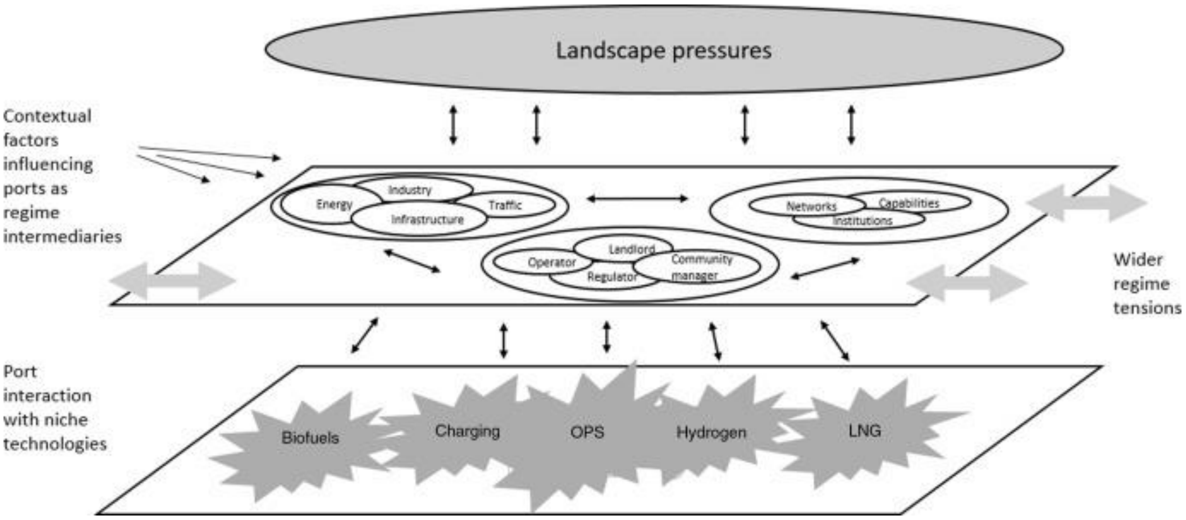


Figure 3. Illustration of the shipping socio-technical system and the role of ports as hybrid actors between niche technologies (e.g., renewable and alternative fuels) and the incumbent regime. From Damman and Steen (2021). Shared under a [CC BY 4.0 license]

Damman and Steen (2021) further summarize, as a theoretical background to their case study, how the role of ports has evolved historically. From a past of being regarded as public property, ports are increasingly adopting a commercial aim. The port authority of today could be seen as a development company, central to the management of the port (Damman & Steen, 2021).

In terms of future role, there is a window of opportunity for port authorities to position themselves as active frontrunners in the transition. This was found to be the case for the Port of Oslo[1], studied by Bjerkan and Ryghaug (2021). The authors explored the transition pathways of Port of Oslo and Port of Kristiansand, where the Port of Oslo was seen as a proactive leader contributing to systemic change to a larger extent than what could be observed in the Port of Kristiansand case. The Port of Oslo's deemed success in transitioning was attributed to performing better in key social processes required for socio-technical systems change. Firstly, the Port of Oslo built strong and committed networks, where all actors involved were actively questioning the commercial aim of ports and passive involvement of the local cities and were instead open to new perceptions about their future role and the distribution of power. The role of Port of Oslo was then changed so that it would be accountable for the emissions from the port. The Municipality of Oslo updated the local climate policy to include and target the port, so that the ambitions of the port must match the

[1] The Port of Oslo is a municipally owned enterprise, whose scope includes being the port authority, landowner and port operator (Port of Oslo, n.d.).

ambitions of the city. In this updated role, the port authority was expected to manage the port community and facilitate collaboration between actors. The role of Port of Oslo thus evolved to include actively engaging with the municipality in spatial planning and setting integrated climate targets (Bjerkan & Ryghaug, 2021).

Malmgren et al. (2023) investigated barriers to the implementation of low-emission marine fuels and how these could be overcome. The results show an interdependent set of stakeholders, where cargo owners, ports, shipping companies and more all influence the final choice of fuel onboard a vessel. The interviewed stakeholders called for legislative requirements forcing shipping companies to adapt and describe a lack of support from the industry when they want to change fuel. The perception was that most of the global maritime cargo transport market adapts exclusively to the lowest cost option that complies with legal requirements. The paper calls for stakeholders, ports as well as cargo owners and shipping companies, to communicate their wish for improved solutions more strongly to collaborate efficiently and adopt effective strategies.

Another prospect for port authorities is to enable and promote sector coupling, i.e., interconnecting energy end-use sectors such as transport, industry and buildings to energy supply sectors via different energy carriers. Urban et al. (2024) interviewed actors and experts involved with the shipping industry and sector coupling in Sweden, such as shipping companies, actors from forestry, fuel producers, port authorities and shipping company associations, on themes like opportunities for strategic partnerships to enable sector coupling. The informants considered sector-coupling to be a precursor for decarbonization of the shipping industry, because new sector dependencies would be created along the emergence of new value chains, e.g., for fuel production using biogenic waste or captured CO_2. Moreover, ports (as port authorities and as physical nodes) were seen as hubs necessary for sector coupling, capable of gathering and coordinating energy networks and actors, facilitating the extensive collaboration required to source the right technologies and competencies and to leverage more resources. In this context, the authors additionally highlighted that collaboration with local energy companies was crucial (Urban et al. 2024). This is also in line with findings in Bjerkan and Ryghaug (2021) who highlighted the informants' call for the role of ports to be extended to the connection to the hinterland and engage more actively the energy and the transport sector.

The role of ports (referring to the cluster of organisations performing all port functions) in the energy transition could, according to Damman and Steen (2021), be summarised into these main categories:

1) The role of regulators, enforcing speed reductions and sanctioning ships with poor environmental performance through fees and limited time at berth;
2) The role of landlords (and thus responsible for port infrastructure), decreasing the perceived risks of innovation by testing new technologies at the port;
3) The role of community managers: through advocacy and creating forums (e.g., port user forums) and building networks.

However, the authors also note that the potential role and scope of a specific port and port authority depend on several localised interdependent physical and non-physical factors. Physical factors include pre-existing infrastructure, traffic, access to renewable energy and impact of local industries. These physical aspects interact with socially constructed factors such as *networks* (collaboration between actors across sectors and geographies), *capabilities* (human resources and their competence) and *formal and informal institutions* (cultural context and history and strategies of the local governments) (Damman & Steen, 2021). The role must therefore be tailored to these preconditions to achieve the most optimal strategy in the transition.

1.3. Driving forces for changes and market aspects

A global shift towards a more efficient, cleaner and less carbon emitting transport system has been ongoing for many years. However, the shipping sector, being international, has fallen behind the development of land-based operations within Europe (European Maritime Safety Agency, 2021). Until recently, there were few and non-strict measures in place to phase out greenhouse gases (GHG) from ship operations (Prussi et al., 2021). Fuels to ships in international as well as domestic traffic are sold without any taxes and without costs connected to carbon or other emissions (Fridell et al., 2022). However, this will change dramatically with several measures connected to the EU Fit for 55 packages. Shipping will be a part of the European Emission Trading System (EU ETS) from 2024, the directive FuelEU Maritime stipulates how the greenhouse gas intensity of fuels used by the shipping sector will gradually decrease over time, and the alternative fuels infrastructure regulation (AFIR) stipulates among other things under which circumstances ports needs to offer OPS connections (i.e., onshore power supply). All in all, many of these directives and regulations sets the path towards a more sustainable shipping sector.

The EU Fit for 55 packages include ships calling European ports (European Parliament and Council, 2023b). However, for policy instruments to be of greater benefit, global policy instruments are required (Fridell et al., 2022). Many regulations are now also discussed by the International Maritime organization (IMO), the United Nations specialized agency with responsibility for the safety, security, and environmental aspects of international shipping (MEPC, 2023a). Forthcoming regulations are further described in *Chapter 3.2 National, EU and IMO Polices and EU funding programs*.

Another driving force is linked to the sharp increase in the number of companies around the world setting voluntary climate goals. One example is the Science-Based Targets Initiatives (SBTi, 2024), where committed companies must reduce their emissions to meet the goals of the Paris Agreement – limiting global warming to 1.5°C above pre-industrial levels. This is an important driving force for companies to also reduce their transport emissions if Scope 3 is included in their targets (Malmgren et al., 2023). In December 2023, more than 6 800 companies were committed globally to SBT initiative, including 309 Swedish companies, see Figure 4. As many as 97% of the Swedish companies have also included Scope 3 emissions with reduction targets for inbound and outbound goods transport (SBTi, 2024).

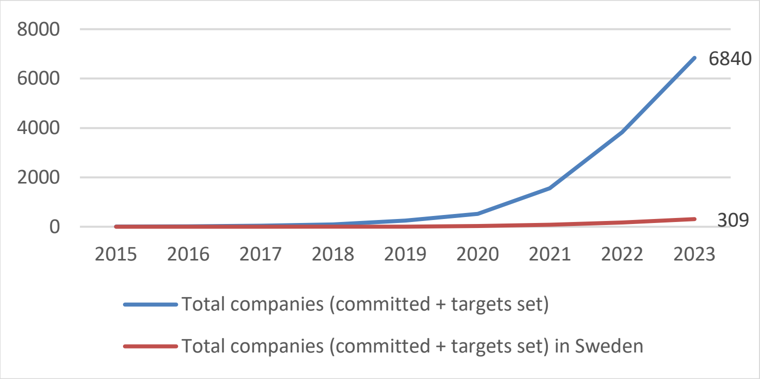


Figure 4. Number of companies committed or with Science-Based Targets globally and in Sweden (2015 until December 2023).

1.4. Introduction to the report

This report consists of an executive summary, followed by this introduction. The next chapter includes methodology, followed by Chapter 3 with the low-carbon fuels and energy carriers for shipping, described from technical, economical, logistics, legal, safety, and environmental point of views. This also include a description of national, EU and IMO Polices and EU funding programs, and development over time. Chapter 4 focus on electrification of barges for inland waterways in the case of the Nemunas River in Lithuania, and Chapter 5 on a green bunkering and charging strategies for Swedish ports. To be able to generalize the results, guidelines for 1) emission free inland waterways and 2) the development of a bunker and charging strategy for ships, are included in Chapter 6. Conclusions and the way forward are presented in Chapter 7, and acknowledgement in Chapter 8.

The focus in this report is on the role of port authorities, but also other perspectives are important, as a shift from fossil fuels to low-carbon fuels require collaboration among many actors. Therefore, we have expanded the scope to also involve the perspectives of shipping companies, terminal operators, energy companies/producers, technology providers and authorities.

IVL Swedish Environmental Research Institute is the author of Summary and Chapter 1, 2, 3, 5, 6.2, 7 and 8, while Lithuanian Inland Waterways is the author of Chapter 4 and 6.1.

2. Methodology

The following methods have been used for collecting data and information for the analysis of low-carbon fuels and development of the bunkering and charging strategy:

- Literature reviews,
- Interviews with different actors,
- Collaboration and knowledge sharing at workshops and meetings with representatives of other ongoing research projects, government assignments and industrial initiatives,
- Assessments of feasibility, environmental aspects, and techno-economic systems of low-carbon fuels production in a Swedish setting and specific market segment, and
- Assessments of energy needs of vessels calling at Swedish ports.

2.1 Literature reviews

Literature reviews include scientific papers, grey literature, scientific- and non-scientific reports, websites, sustainability reports, news articles, authority investigations and other published material. Previous research was examined and further built upon, and additional information was collected of ongoing projects and initiatives in the field of shipping, energy, and low-carbon fuels.

2.2 Interviews

The different actors from ports and shipping companies have been interviewed and asked about the fuels being used in their present operation, how these fuels are bunkered today, and about present infrastructure related to fuels. Also, the infrastructure and use of shore-to-ship electricity connections has been mapped. Ports and shipping companies has also been asked about their present short-term plans (within the upcoming five years) for renewable fuels as well as their more long-term plans and predictions. The interviews have been performed as semi-structed with an interview template with follow-up questions related to areas of interest.

The interviews with port and terminals operators have focused on larger ports in Sweden, but some smaller ports have also been included. Swedish ports that have been interviewed are: *Port of Gothenburg, Port of Stockholm* including *Hutchison Ports Stockholm, Port of Trelleborg, Port of Malmö, Port of Karlskrona, Port of Helsingborg, Port of Norrköping, Port of Gävle, Port of Gotland* - incl. *Visby* and *Port of Slite*, *Port of Stenungssund, Port of Sundsvalls, Port of Piteå, Port of Skellefteå* (including *Shorelink*, terminal operator in Piteå, Luleå and Skellefteå), *Port of Umeå* (including *Kvarken Ports*, terminal operator in Umeå and Vasa), *Port of Halmstad*, *Port of Karlskrona*, *Port of Hallstavik, Port of Iggesunds, Port of Södertälje, Port of Strömstad, Port of Landskrona, Port of Oxelösund* and *Port of Örnsköldsvik*.

The interviews have only covered a few Swedish shipping, because the project group already had much of the information needed to be able to perform the necessary assessments from different other sources such as earlier and ongoing development projects in partnership with shipping companies calling Swedish ports. Further, our close collaboration with many of the shipping companies operating the Swedish coast, mean that we have a good understanding for their plans and approaches. Interviewed shipping companies specifically for this study are: *Wallenius SOL and Wasaline.*

To create synergies, save resources and not take up too much of the ports' time, the interviews with terminal operators and ports have been carried out in collaboration with RISE Research Institute of Sweden (Swedish research creating sustainable growth | RISE). They had an ongoing sister project that collected information about port infrastructure, so the two questionnaires were combined and the ports were divided among us to cover a larger share of the ports. Consequently, we reach out to approximately 25 ports, representing in total around 90% of the total fuel consumed by ships in domestic and international services. Main public ports in Sweden are shown in Figure 5.

Interviewed energy companies are: *OX2, SoutH2Port and Skyborn, Uniper, Umeå Energi, Flexens* (Finland) and Svea Vind Offshore. Discussions has also been held with *Liquid Wind*.

Figure 5. Swedish ports. Sweden has one of the Europe's longest coasts of approximately 2400 km, from Haparanda in the north to Strömstad in the west. Source: Ports of Sweden.

2.3 Collaboration and knowledge sharing

Collaboration and knowledge sharing have been an important part of this work, both with other research projects, but also government assignments, industrial projects or ventures, pilot studies, etc. Ongoing or recently finalised research projects at IVL have also been an important source of information. Examples of collaborations with other projects include: *Nordic Roadmap – Future Fuels for Shipping* (Partners: DNV, Chalmers, IVL, MAN, etc.), *Green maritime corridors* (Swedish Transport Administration's Governmental assignment), Lighthouse's Focus groups *Fossil free shipping* and *Ports (https://lighthouse.nu/sv/verksamhet/fokusgrupper), H2AMN (partners: IVL, Port of Gothenburg, Statkraft, Luleå University, etc.)* and Costs for decarbonizing shipping (national research study, project leader IVL). HOPE – analysing hydrogen fuel cells solutions in shipping (Partners: IVL, Stena Line, Power cells, University of Iceland, SINTEF).

2.4 Assessments of feasibility, environmental aspects, and techno-economic systems of hydrogen-based production

A key part of the project has focused on knowledge generation and analysis of how different technology options can perform on the market. The technologies feasibility, costs and environmental impacts have been analysed using different methodologies, but all have taken an assessment approach. The individual methods are described below.

2.4.1 Feasibility assessment

The feasibility assessment and forecasting regarding technical development were primarily conducted through synopsis of knowledge from previous project in combination with similar analysis from literature.

2.4.2 Environmental assessment

The environmental assessment was performed using a life cycle assessment (LCA) approach focused on fuel production and use in a Nordic setting. The system boundaries for the assessment include the full life cycle for the fuel and propulsion system, including raw material extraction as well as end-of-life. Capital goods not related to the energy system, such as hull and propeller, has not been considered. The analysis includes emission inventory data and fuel consumption data gathered from different studies as well as from discussions with engine manufacturers and industry stakeholders. Data for not yet mature technologies has been forecasted using the methodology presented in Kanchiralla (2023). The full goal and scope of the study is presented in Brynolf et al. (2023).

2.4.3 Methodology for techno-economic assessment

This section describes the methods used in the techno-economic assessment and scale-up of industrial processes, the estimation of capital cost using the factorial method and how fixed and variable operational costs are estimated. Furthermore, the economic evaluation and assumptions made are described.

2.4.3.1 Estimation of capital cost

The factorial method is common to estimate the installed capital cost of a chemical process or plant. The method requires the costs of the major equipment items of the process, while other costs are estimated as factors of the major equipment cost. Therefore, the accuracy of the method is highly dependent on the accuracy of the cost data related to the major equipment items.

Provided that detailed equipment costs are available, a class 3 estimate can be done (Towler et al., 2013). However, it is most likely that the estimation leads to a class 4 estimate. Towler et al. defines class 3 estimate as a definite estimate with an accuracy of ±10-15% and a class 4 estimate as a preliminary estimate with ±30% accuracy used for choices between design alternatives. In present work, the method is used to evaluate different technologies to compare alternatives to each other as well as to give insight into the contribution of different factors to the overall cost for the different alternatives.

The other costs accounted for by the factorial method are inside battery limit (ISBL) costs and outside battery limit (OSBL) costs, as well as design and engineering and contingency. ISBL costs, except the major equipment costs, include equipment erection, piping, instrumentation, and control, electrical, civil, structures and buildings, and lagging and paint. OSBL costs include costs of additions that must be made to the site infrastructure such as for example power generation plants, cooling towers, tank farms and workshops.

The factors are based on historical data of the cost of plants and can be found for different process types (fluids, fluids-solids, solids). Furthermore, the factors are based on plants built from carbon steel. However, if other materials and alloys are required, additional factors are included to account for the change in cost. The lang factor used in this work is 5.04 and is proposed by Seider et al. (2017) to be used for fluid processing plants. The fixed capital investment (FCI) is calculated as presented in Equation 1,

$$FCI = 5.04 \sum Costs_{Equipment} \qquad \text{Equation 1}$$

Cost escalation was done by using the chemical engineering plant cost index (CEPCI) to bring costs of equipment to equivalent costs 2023. In order to scale the cost data to desired scale, based on reference costs data, the so called sixth-tenth rule (Towler et al., 2013) was used (Equation 2),

$$C_{new} = C_{Ref}\left(\frac{Cap_{new}}{Cap_{Ref}}\right)^{m} \qquad \text{Equation 2}$$

where C_{new} is the new cost, C_{ref} is the reference cost, Cap_{new} is the capacity that the equipment is scaled to, Cap_{ref} is the reference capacity and m is an exponent that may vary depending on equipment, but on average is 0.6. The exponents used in the different cases are presented in following sections.

2.4.3.2 Estimation of production cost

Production cost includes variable and fixed costs. The variable costs include raw material, utilities, waste disposal and consumables as well as packaging and shipping. The fixed cost of production includes cost for labour and supervision, maintenance, taxes, general plant overhead, cost of licenses and royalty payment, insurances as well as capital charges. The variable costs are either estimated from literature or obtained from the plant material and energy balances combined with cost data for the raw material and utilities. The fixed costs can be estimated according to Table 1.

Table 1. Factors for estimation of fixed operational costs (Seider et al., 2017).

Labor related	
Work hours	2080 h/yr
Salary	32.5 EUR/h
Shifts	5
Operators per shift	1-2 per process section depending on size
Direct wages and benefits (DW&B)	Based on work hours, salary, shifts and operators per shift.
Direct salaries and benefits	15% of DW&B
Operating supplies and services	6% of DW&B
Technical assistance to manufacturing	55487 EUR/(operator/shift)-yr
Control laboratory	60112 EUR/(operator/shift)-yr
Maintenance	
Wages and benefits	3.5% of FCI (Fixed capital investment)
Salaries and benefits	25% of wages and benefits
Material and services	3.5% of FCI
Maintenance overhead	5% of wages and benefits
Operating overhead	
General plant overhead	7.1% of M&O-SW&B[a]
Mech. Department services	2.4% of M&O-SW&B
Employee relations department	5.9% of M&O-SW&B
Business services	7.4% of M&O-SW&B
Property taxes and insurance	2% of FCI
Depreciation	8% of FCI
Royalty	3% of product sales

a) M&O-SW&B = DW&B + Direct salaries and benefits + Maintenance

2.4.3.3 Economic analysis

The economic analysis is done through a discounted cash flow model with an assumed plant life of 30 years. The discount rate i_d is calculated according to Equation 3,

$$i_d = \frac{1}{(1+i)^t} \qquad \text{Equation 3}$$

where t is number of years, and i is the annual real interest rate. The annual real interest rate is calculated from the nominal interest rate and the annual inflation rate according to Equation 4,

$$i = \frac{i' - f}{1 + f} \qquad \text{Equation 4}$$

Where i is the nominal interest rate and f is the annual inflation rate. Based on (Towler et al., 2017) it is assumed that 30% of the total fixed capital investment (TFCI) is invested the first year, 60% the second and 10% the third year. Production is assumed to start year 3 with 30% production, reach 75% production year 4 and full production year 5. A straight-line depreciation was used. The fixed operating costs are assumed to be 100% from production start, while the variable operating costs increase with the same rate as the production. The working capital is assumed as 17.6% of the Fixed capital investment (FCI) and is invested at start of production (year three) and returned the last year of production. The cost of land is assumed to be 2% of FCI and the start-up cost is set to 15% of FCI. The net present value (NPV) is calculated according to Equation 5,

$$NPV = \sum_{t}^{N} i_d(C_{CapEx} + C_{WC} + C_{OpEx} - C_{Income}) \quad \text{Equation 5}$$

where N is the plant lifetime, t is the number of years, C_{CapEx} is the total fixed capital investment at year t, C_{WC} is the cost of working capital at year t and C_{OpEx} is the variable and operating costs at year t. By letting the price of the product vary until the NPV is equal to 0 the levelized cost can be calculated.

2.5 Energy demand of vessels calling at Swedish ports

The methodology used for roughly estimating total energy usage of vessels calling at Swedish ports is based on the methodology developed during the HOPE project (HOPE, 2023). Port call statistics for all Swedish ports in 2022 were received from the Swedish Maritime Administration (Swedish Maritime Administration, 2023). For each port call, the distance between departure port and arrival port was calculated according to the distance at sea (SeaRoutes, 2022) multiplied by a calculated energy usage per NM. The energy usage per NM is calculated from the MRV[2] (THETIS-MRV, 2022) reported CO_2 emission factors, whose magnitudes are used as signatures for specific fuels or fuel blends. This allows the fuel usage to be back calculated in conjunction with other information such as ship and engine types, service speed, number of engines, etc. Once the quantity of fuel is known, the energy can be calculated from the known fuel energy density. For both domestic and international traffic, the fuel consumption is shared equally between the ports, meaning that energy for half of the trip is allocated to arriving port and the rest the departing port. Thus, all fuel consumptions between domestic ports are included in the analysis, but only half of the consumption between a Swedish port and any other international port.

2.6 Analysis of uncertainties

Data and assumptions in calculations and scenario analysis presented in this report are based on best possible basis known by the authors, all made with efforts to represent an accurate picture of the present situation. The same goes for predicted future development where efforts have been made to give a sound and as likely as possible description of the progress. However, the available data base varies greatly in range between different sources and development is progressing rapidly, indicating that calculations and qualitative analysis in this report can differ from actual development over time. Within some calculations, sensitivity analyses have been added to show the influence specific parameters will have on the results.

Sensitivity analysis has been carried out for the single cost parameters (e.g. electricity price, interest rate, etc.) of methanol, hydrogen and ammonia to capture the impact of on the levelized cost as well as the required CO_2-price to make the production economically feasible.

When calculating total climate impact for alternative marine bunker fuels from well-to-wake compared to fossil fuels alternatives, different engine systems were considered including 2-stroke, 4-stroke, and fuel cell propulsion, as indicated with error bars in Figure 7.

[2] MRV stands for Measurement, Reporting, and Verification of ship emissions, and the system will serve as the basis for carbon tax determination though the EU ETS and FuelEU Maritime regulations.

3. Low-carbon shipping

The need for the phase out of fossil fuels and reducing greenhouse gases from ships and port operations through carbon capture in combination with increased energy efficiency is today an accepted fact.

Almost all fuels used for shipping today is of fossil origin. DNV (2023a) reports that 99.9% of the fuel used for ships ≥5 000 gross tonnage in 2021 was fossil oil or gas. However, this is expected to change in the coming years due to upcoming regulations from IMO and EU addressing the 2050 net-zero GHG targets for the shipping sector. The uptake will be slow the forthcoming years due to lack of fuels and moderate requirements (Malmgren et al., 2023; Urban et al., 2024), but global outlooks for future fuel demand predict substantial increases for sustainable fuels in the forthcoming decades. This includes biofuels (e.g., HVO and LBG), methanol, hydrogen, ammonia but also battery electric and wind propulsion.

The choice of which fuel and technology solutions that suits the specific vessel and port application best is often not given and different pros and cons with the different solutions needs to be taken into consideration. As per today, the most promising low-carbon fuels for shipping within our region, are methanol, hydrogen and ammonia based on for example findings in Nordic Roadmap project report (Nygård Basso et al., 2022a). In addition, also electrification will be assessed within this study as it is assessed to also be an important energy carrier for decarbonisation in relation to ports and vessels within ports. Different solutions will all have their own barriers that needs to be handled, being mainly safety for ammonia, low volumetric density for compressed hydrogen and the need for biogenic or other non-fossil carbon dioxide to produce e-methanol, as examples. Increased costs in relation to the traditional use of fossil marine fuels is a main barrier for an introduction pace faster than the outlined requirements within for example FuelEU Maritime (see *Chapter 3.2 National, EU and IMO Polices and EU funding programs*)

Within the work of this report, the aspects of the fuels will be described and discussed and a future scenario for the bunkering in Swedish ports will be outlined and assessed. Prerequisite for the transfer towards low-carbon fuels will however be energy savings. Future low-carbon fuels will be more expensive which will drive efficiency gains but also increasing energy efficiency requirements from IMO will contribute to industry efforts to decrease energy demand.

This chapter describes and analyse the most promising low-carbon fuels in terms of general parameters and performance, maturity levels, present and expected future production capacity, infrastructure requirements, sustainability performance (LCA), techno economical as well as safety performance but also in relation to national, EU and IMO policies as well as expected development over time.

3.1. Description of alternative fuels and charging facilities

The fuels that more technically, economically and in relation to sustainability will be assessed within this work are methanol, hydrogen, and ammonia along with battery electric propulsion solutions. This shall not be seen as an evaluation that other fuels would be out of scope as decarbonisation solutions for ships. For example, is liquified biogas (LBG or LBM, also sometimes mentioned as bio-LNG) a fuel with good sustainability and greenhouse gas performance, can be used in all ships with engines that today can run on LNG without any engine modifications and has the potential to be produced in large quantities in countries like Sweden. Today, about 6 percentage of all ships (measured in gross tonnage capacity) can be fuelled by LNG or LBG, and of all vessels in order, over 40 percentage of the vessel capacity will be able to run on LNG or LBG (Grahn et al., 2024). An estimate for the Swedish potential to produce biogas / LBG made in 2022 showed that the production capacity of sustainable produced biogas in Sweden could be increased with some 25 TWh annual fuel production which is in line with all marine bunker fuel sold in Sweden per year. (Jivén et al., 2022). There is also always a possibility for ship owners with tradition diesel engines to buy a bio-diesel such as HVO which almost all diesel engines can run on. However, the total supply of HVO is very limited compared with the total fuel consumption of the shipping sector, which means this is a marginal solution. Similarly, electro-diesel would also not require any specific modifications but comes with a high cost per energy content compared to other solutions such as electro-methanol or ammonia. An overview of selected alternative marine fuels is shown in Figure 6.

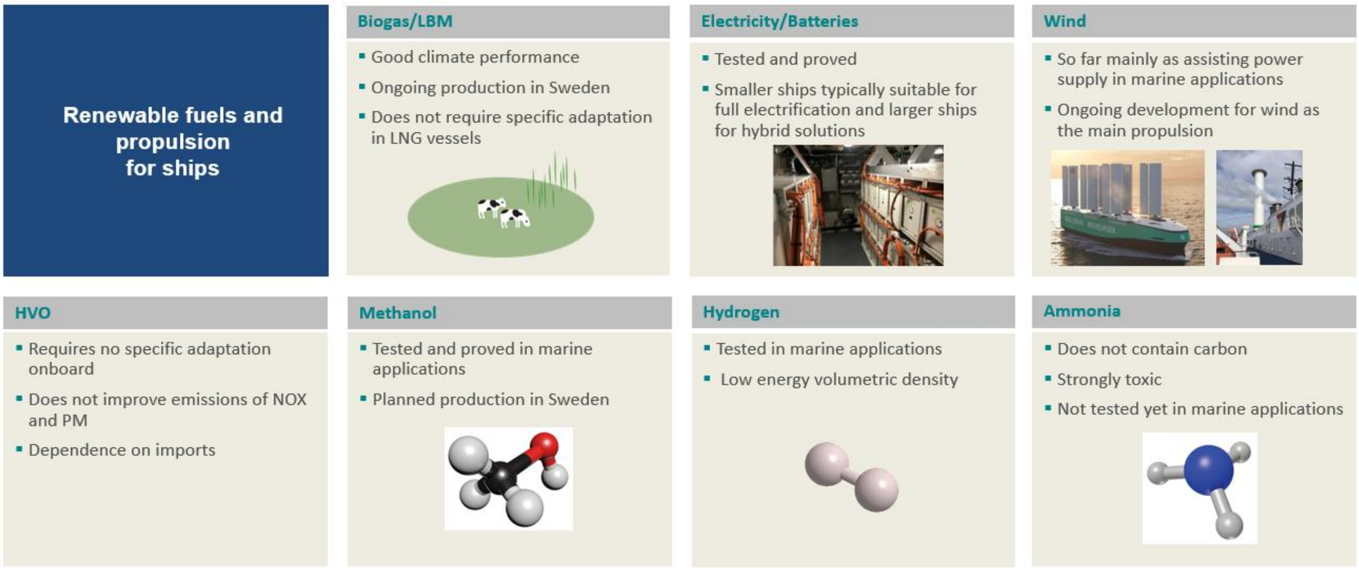


Figure 6. Overview of fuels to replace existing fossil fuels and measures to reduce the greenhouse gases of shipping.

Methanol is seen as a promising marine fuel. Today some 0,05 percentage of the world ship fleet (measured in gross tonnage) can be fuelled with methanol but about 8 percentage of ships in order (measured in gross tonnage) will be able to run on methanol (DNV, 2023a). Ships require engines that are suitable for methanol which major marine engine manufacturers are able to deliver. Typically, methanol engines are dual fuel engines also able to run on fossil fuels such as Marine Gas Oil (MGO).

Ammonia has the benefit of not containing any carbon, hence not requiring carbon dioxide within the production process, and not emitting carbon dioxide within the combustion process. It is also a less complex molecule than methanol and is expected to be produced at lower cost per energy quantity than for example methanol. On the other hand, ammonia is truly toxic and requires stringent safety measures in the whole supply chain as well as on-board the ship. For an assessment of the technical feasibility of ammonia and hydrogen for three case ships, see Kanchiralla et al., 2023 which find that ammonia and hydrogen is feasible for the assessed ships from a safety perspective but that several measures are needed.

The American Bureau of Shipping has recently published an updated market outlook for alternative fuels (American Bureau of Shipping, 2023). Included ship types are oil and chemical tankers, dry bulk carriers, containerships, LPG, LNG, car carriers, general cargo, RoRo, RoPax, and cruise ships. The anticipated shares of both methanol and ammonia have increased since the previous update. Methanol will enter the market somewhat earlier than ammonia resulting in a market share of about 8% methanol and 2% ammonia in 2030. This is expected to increase to approximately 25% methanol and 15% ammonia in 2040.

Similar trends have been reported by MAN Energy Solutions (2022), that highlight a transition to enhanced fuel diversity for shipping. The combined share of methanol and ammonia is estimated to be around 10% in 2030, followed by an increase to approximately 18% of each fuel in 2040. Only very limited amounts of hydrogen fuel are included in the forecast. In 2050, shipping will, according to MAN Energy Solutions, demand 300 million tonnes (Mton) of ammonia, 225 Mton of methanol, 80 Mton of methane and 180 Mton of single fuel (usually HFO, MDO, biofuels and synthetic fuels). Furthermore, the report states that engine technology is no barrier to achieve CO_2 reductions in the shipping sector.

The Maritime Forecast to 2050 presented by DNV (DNV, 2023a) shows that ships on order consists of 51% alternative fuels by gross tonnage, compared to only 6.5% of existing ships using alternative fuels. The alternative fuels mainly contain LNG (40%) but also methanol (8%), LPG (2%) and battery/hybrid solutions (0.8%). The lack of ammonia fuelled ships in the order books also indicates a later introduction of this fuel type compared to methanol. The demand for carbon-neutral fuels in shipping is estimated to 17 Mtoe in 2030 and about 100 Mtoe in 2040. No detailed information for different fuel types is presented.

The amount of alternative fuel that will be available for the shipping market is uncertain. A significant number of projects for carbon-neutral fuel production are ongoing or planned, around 2 200 according to DNV (DNV, 2023a). However, most of these projects are at an early stage and other markets such as chemical industries and aviation are also potential consumers.

The Swedish organization *Fossilfritt Sverige* has published a national roadmap for fossil free shipping (Fossilfritt Sverige, 2019). This report also stresses the low availability of alternative fuels, combined with a high cost, as being one of the main hurdles for low-carbon shipping. Promising alternatives that are mentioned include LNG and LBG, HVO, methanol, battery technology and wind-assisted propulsion. Another important aspect that is stated concerns encouragement and protection of early movers, for example by providing governmental support systems.

In a report from the Nordic Roadmap project, the theoretical maximum potential for alternative fuels in Nordic shipping is presented (Nordic roadmap, Task 2B). The analysis is based on ship activity patterns and ship sizes in 2019 combined with an assumption that only hydrogen, ammonia and methanol will be used as alternative fuels for all Nordic domestic shipping, intra-Nordic shipping and half of the traffic from Nordic countries to nearby regions. Considering each fuel's feasibility to cover the evaluated traffic, the theoretical maximum amounts to 0.7 million tons of hydrogen or 9.55 million tons of ammonia or methanol. This study also conducts a mapping of existing and planned zero-carbon fuel production in the Nordic countries within 2030. The results show a sufficient supply of hydrogen if all planned projects would reach the expected production capacity. However, methanol and ammonia production only cover about 43% of the technical feasibility estimated for shipping. An important factor to consider is the uncertainty of production shares for maritime use, no information on this is presented. For example, the Swedish fossil-free steel industry will likely use substantial quantities of the green hydrogen production.

3.1.1 Technical description and maturity level

In the following section a technical description of different maritime fuels as well as maritime electric motors are described. The current status, maturity level, advantages and disadvantages related to the use of methanol, hydrogen and ammonia as well as electric motors are presented. The technology readiness levels (TRL) for bunkering and operation using the different alternatives are presented in Table 2, TRLs are based on a scale from 1 to 9 with 9 being the most mature technology.

Table 2. Technology readiness level (TRL) for bunkering and usage of alternative technologies for shipping.

Technology	Bunkering	Vessel operation	Reference
Electrification	6	Marine battery systems: (5-7)	(International Chamber of Shipping, 2021)
Methanol	9	Internal combustion engines (ICE): 6-8	(Harmsen et al, 2020), (Frelle-Petersen et al, 2021)
Hydrogen	6	Fuel cell: 6-7 Internal combustion engines (ICE): 5-6	(Hansson et al, 2023), (Frelle-Petersen et al, 2021)
Ammonia	8	Fuel cell: 4-5 Internal combustion engines (ICE): 4-5	(Hansson et al, 2023), (Frelle-Petersen et al, 2021)

As can be seen, the use of methanol and hydrogen has reached a higher TRL than ammonia, however the TRL of hydrogen bunkering is lower than methanol and ammonia, which are both close to a TRL representative of commercial use. The TRL for electric propulsion systems is equal to that of hydrogen both in regard to bunkering and operation.

3.1.1.1 Electrification

The use of electric motors in smaller ships and ferries could, in cases that are suited for the application, already be economically feasible with the incentives that are in place today (Jivén et al., 2022). The use of batteries on smaller vessels on fixed, short routes is an example of a case where electrification could be a suitable option.

The technology is still developing but can be considered a mature technology since it has been applied to both small- and large-scale shipping. The on-board challenges related to electrification are weight, cost, reach and charge capacity. To combat these challenges, it is important to target the battery size (Jivén et al., 2022). However, this means that the vessels need to have the possibility of fast charging of batteries during the operational time of the day.

This, in turn, gives rise to onshore challenges related to charging possibilities. Lack of electrical power in connection to the charging stations could result in extra establishment costs. The costs of the actions necessary to establish enough electrical power needed for to be able to meet the demand of, especially larger sized electrified vessels, could result in significant costs. In addition to the extra establishment costs, there could be competition for the available electrical capacity with other actors.

Due to the low energy density in currently existing batteries in comparison to liquid fuels, full electrification of larger ships that travel long distances does not seem like a feasible future development (Jivén et al., 2022). However, for shorter distances between fixed ports, electrification might be a feasible future route. Further, batteries as a supplementary energy source to reduce fuel consumption on-board and improve energy efficiency have become increasingly common in recent years.

3.1.1.2 Methanol

Methanol has been proven to be a marine fuel that works well that also results in less emissions of nitrogen oxide (NOx), sulphur and particles compared to traditional marine fuels (Jivén et al., 2022). Furthermore, methanol has a relatively low capital investment for newbuilds and retrofit since it does not require pressurization or cryogenic fuel tanks and systems (DNV, 2023b). Existing fuel tanks or even ballast water tanks may be used for methanol by applying specific internal coating. However, a downside of using methanol is that it takes about 2.5 times more space than oil tanks and has lower energy density.

Methanol is not an environmental hazard fuel, but during bunkering toxic vapours escape, resulting in the need for gas hazard zones (DNV, 2023b). A major challenge related to methanol as a marine fuel is that fossil methanol increases the life cycle GHG emissions by about 10% compared to MGO. Green methanol is not available in significant quantities today. There are plans of production facilities for renewable methanol as shipping fuel. However, compared to the demand the volumes are still low (DNV, 2023b).

3.1.1.3 Hydrogen

Hydrogen can be produced by electrolysis of water in an electrolyzer. The hydrogen can thereafter be used in hydrogen fuel cells or hydrogen combustion engines, which are under development. In addition to electricity, only steam and heat is generated from fuel cells. In the combustion engines, no CO_2 is produced since the fuel does not contain carbon, resulting in low emissions in comparison to more conventional combustion engines.

There are, however, several challenges of the usage of hydrogen as fuels. Hydrogen is light and requires a lot of storage space compared to liquid fuels. Hydrogen can be stored in high-pressure storage or be liquified in order increase the energy density. However, high pressure storage does still require at least 10 times more space than marine gasoil (MGO) (Jivén et al., 2022).

Liquid hydrogen further increases the energy density of the fuel, however, to keep hydrogen liquid a temperature of -253°C is required, which in turn require well isolated tanks. Furthermore, it is required that the hydrogen is not stored for too long period of time since the low temperature requirement will result in that the hydrogen will evaporate as it is heated by the surrounding.

From an energy efficiency perspective, the storage of hydrogen gas at high pressure is the better option since the liquefaction of hydrogen requires a lot of energy. State of the art hydrogen liquefaction technology has a power consumption of 13-15 kWh/kg hydrogen. With an energy content of hydrogen of 33.3 kWh/kg hydrogen, liquefaction corresponds to 39-45% of the hydrogen energy content (Geng et al., 2023). Compression of hydrogen to 700 bar requires about 6 kWh/kg hydrogen, which corresponds to about 18% of the energy content of hydrogen.

The storage of hydrogen is the main onboard challenge related to hydrogen. Other challenges related to hydrogen as a fuel are guidelines and methods to manage hydrogen in a safe way. Hydrogen has a very broad flammability range in air compared to for example natural gas and therefore it is important to that there are clear safety rules and guidelines for the handling of hydrogen.

Onshore challenges related to the use of hydrogen as a maritime fuel include development of infrastructure, high investment, and operational costs, as well as costs related to electrolyzers. Furthermore, hydrogen from electrolyzers is highly dependent on the production of renewable electricity. An increased use of hydrogen from electrolyzers therefore requires increased production of renewable electricity. In addition, the lack of clear rules and regulations constitutes a barrier for investments in production and usage of hydrogen.

In conclusion, there are several challenges related to the usage of hydrogen as a maritime fuel. Technology maturity level is lower than for biofuels and solutions connected to electrification and there is a lack of clear guidelines, rules and regulations for production of, and safe handling of hydrogen. Continued development of applications, as well as guidelines and rules, for the use of hydrogen in the maritime sector, is therefore necessary if it should be a feasible option.

3.1.1.4 Ammonia

Green ammonia can be produced from green hydrogen through the Haber-Bosch process (Duncan et al., 2023). The green hydrogen is produced from electrolyzers via renewable electricity and is thereafter reacted with nitrogen at high temperature (350-500°C) and pressure (150-300 bar) in the presence of an iron-based catalyst. One of the advantages with the use of ammonia as a fuel is that it does not contain carbon and does therefore not emit any CO_2 when combusted (Duncan et al., 2023). Furthermore, it can be used in diesel engines adapted for ammonia and in certain fuel cells (Jivén et al., 2022).

The main problem related to ammonia is its toxicity. Even minor leakage therefore involves high risks. Ammonia has been produced and used in other industries, such as the fertilizer industry, for a long time (European Maritime Safety Agency, 2022). There is experience in shipping ammonia as cargo, and therefore there are already some safety procedures in place. However, the use of ammonia as a fuel is new and would require additional regulations in order to reduce the risk of handling ammonia (European Maritime Safety Agency, 2022).

Additionally, the engines for the use of ammonia are under development. The challenges related to combustion of ammonia is the possible emission of nitrogen oxide (NOx) and nitrous oxide (N_2O). Furthermore, compared to MGO and LNG, the energy density of ammonia is low (12.7 MJ/l). Ammonia also requires more storage space than MGO and more or less the same as LNG.

The total cost of ownership for green ammonia-fuelled ships are about 2.5 – 3 times higher compared to conventional fuelled ships. However, this gap might be reduced as the production and the installation costs required for ammonia, are reduced and carbon prices for fossil fuels increased (European Maritime Safety Agency, 2022).

3.1.2 National production capacity

The transformation towards renewable fuels including hydrogen-based fuels in the shipping sector will require a significant fuel production capacity. This needs to be developed over time. Hydrogen and electrofuels production plans in Sweden have been mapped and presented in Nygård Basso et al (2022b), Stenersen and Lundström (2023) and Fagerström et al (forthcoming). In total around 25 projects have been identified and the majority is about hydrogen. However, as confirmed by publicly available communication around specific projects, direct communication with project owners (such as interviews), most of the projects focus on industrial applications such as the use of hydrogen to decarbonize steel production or has a dedicated industry as user and thus not specifically mention ports or the shipping industry as a market. Though, there are some exemptions, see Table 3, with projects that specifically target maritime application.

As seen in Table 3 which presents examples of planned production plants for hydrogen-based fuels, the expansion of methanol and hydrogen production in Sweden is ongoing. Liquid Wind, which is an electrofuel developer, is involved in several ongoing projects (f3 Innovationskluster för hållbara drivmedel, 2023). During 2023, construction of a methanol production plant in Örnsköldsvik with a capacity of 50 000 tonnes of methanol per year began with a planned start year of 2025. In 2023, an environmental permit application has also been submitted for another plant in Sundsvall with a capacity of 130 000 tonnes of methanol per year (with 2026 as planned start year). Liquid Wind also collaborates with Umeå Energi and is planning a third plant in Umeå with a capacity of 110 000 tons methanol per year (f3 Innovationskluster för hållbara drivmedel, 2023). The intended market for the methanol is for all these projects primarily the shipping sector and the methanol is produced from biogenic carbon dioxide and hydrogen from renewable electricity. In terms of hydrogen, ABB, Uniper Sweden, the Port of Luleå, Luleå Energi and Luleå municipality have initiated a cooperation to establish a hydrogen hub in Luleå, to further develop the hydrogen economy in the northern parts of Sweden (ABB, 2021). The project is planning to build a large-scale plant to produce hydrogen via electrolysis intended for industry and maritime applications. Fertiberia is also planning to build a green fertilizer and ammonia production plant in Luleå-Boden around 2025 and the shipping sector is mentioned as a potential user of the ammonia (Invest in Norrbotten, 2023).

It could also be noticed that many of the identified projects in Sweden for production of hydrogen-based fuels (in Nygård Basso et al., 2022b; Stenersen and Lundström, 2023) are in the vicinity of ports or the sea, which imply that they, if realized, potentially could be relevant for ports and the shipping sector in the future.

Table 3. Examples of planned production of hydrogen-based fuels for the maritime sector in Sweden (based on f3 Innovationskluster för hållbara drivmedel, 2023).

Fuel	Plant, owner	Location	Start year	Production capacity per year	Status
Methanol (from hydrogen and biogenic CO_2)	FlagshipONE (Ørsted, Övik Energi, Liquid Wind)	Örnsköldsvik	2025	50 000 tonnes	Under construction
Methanol (from hydrogen and biogenic CO_2)	FlagshipTWO (Sundsvall Energi, Liquid Wind)	Sundsvall	2026	130 000 tonnes	Planned
Methanol (from hydrogen and biogenic CO_2)	Flagship THREE Liquid Wind (Umeå Energi)	Umeå	2026	110 000 tonnes	Planned
Hydrogen, (for industry and maritime applications)	Botnialänken H2 (ABB, Uniper Sweden and the port of Luleå, Luleå municipality)	Luleå	NA	12 000 tonnes	In discussion

In terms of other renewable fuels potentially of interest for Swedish related shipping, there is for example current and planned production of LBG in Sweden with potential use in the maritime sector, see Table 4 (f3 Innovationskluster för hållbara drivmedel, 2023). There is also production of renewable diesel (mainly HVO) and to a minor extent ethanol and biogas (compressed) in Sweden, currently mainly used for other transport related applications.

Table 4. Examples of existing and planned production of biogas liquification plants in Sweden (f3 Innovationskluster för hållbara drivmedel, 2023).

Fuel	Plant, owner	Location	Start year	Production capacity per year	Status
Biogas liquification plant	Tekniska verken	Linköping	2020	max 85 GWh LBG (+ potential expansion)	In production
Biogas liquification plant	Air Liquide, Gasum	Lidköping	2011	NA	In production
Biogas liquification plant	Gasum, Stora Enso	Nymölla	2023	NA	In production
Biogas liquification plant	Gasum	Götene	2025	120 GWh	Planned
Biogas liquification plant	Borås Energi, ST1	Borås	2024		In production
Biogas liquification plant	Gasum	Borlänge	No later than 2027	120 GWh	Planned
Biogas liquification plant	Gasum	Mörbylånga	No later than 2027	120 GWh	Planned
Biogas liquification plant	Gasum	Hörby	No later than 2027	120 GWh	Planned
Biogas liquification plant	Gasum	Sjöbo	No later than 2027	120 GWh	Planned
Biogas liquification plant	Biokraft	Mönsterås	2024	125 GWh	Under construction
Biogas liquification plant	Biokraft	Stockholm	2024	200 GWh	Planned/in prod.
Biogas liquification plant	Biokraft	Skånes-Fagerhult	2025	135 GWh	Planned
Biogas liquification plant	Air Liquide (Lidköping biogas)	Kristianstad	No later than 2028	>100 GWh	Planned
Biogas liquification plant	Gasum	Kalmar	2026	250 GWh	Planned

To what extent future production of hydrogen-based fuels will match the demand in ports, terminals and ships is a delicate question to answer. There are large uncertainties linked to planned production as many of the project are dependent on public support, the future demand for these fuels, the willingness to pay for these products and the supply of renewable electricity (for which for example environmental permits for off-shore wind power parks are needed in some cases). There is also the possibility to import fuels from other countries. Mapping of production plans for hydrogen-based fuels in the Nordic countries is presented in Nygård Basso et al. (2022b) and Stenersen and Lundström (2023) but the situation changes quickly.

The demand for hydrogen-based fuels from the shipping sector is also highly uncertain. Over time, low-carbon fuels will be needed in both ports and terminal operations and for propelling ships. The FuelEU Maritime requirements will demand lower carbon intensity for fuels used on-board ships in European waters which sets some levels for the pace of such demands that can be used as indications of what levels that will be needed (see *Chapter 3.2 National, EU and IMO Polices and EU funding programs*), but that can also partly be met with biomass-based marine fuels. There are also uncertainty factors that can affect the demand for low-carbon fuels needed for ships calling Swedish ports including for example:

- The level of energy efficiency within the operations due to more efficient engines and propulsion potentially being applied with economy of scale, operational measures and for example through wind assistance.
- To what extent ships with international call ports bunker fuels in Sweden or abroad. Where ships bunker depend on a mix of factors such as price and market situation for fuels in ports close to the ships route.

3.1.3 Infrastructure and storage needs

3.1.3.1 Storage of Hydrogen

Hydrogen can be stored in compressed form as gas or liquid, in pipelines and in underground geological formations such as lined rock caverns.

Pressure vessels

For storage of hydrogen in pressure vessels the challenge related to the phenomenon of hydrogen embrittlement occurs (Murakami, 2019). Hydrogen embrittlement is caused due to penetration of hydrogen into metal which causes mechanical damage. The effect of hydrogen embrittlement increased with pressure is increased. To meet this challenge, materials have been developed to allow for significantly higher pressure and more compact storage. Pressure vessels used to store hydrogen are divided into 4 different types (I, II, III & IV) which is dependent on what material is being utilized in the pressure vessel (Danish Energy Agency, 2020).

Type I and II tanks are mainly used for stationary application, while III and IV are used for mobile applications (such as on-board fuel storage). Type I consists of metallic walls, type II consists of metallic walls and is partially wrapped in composite material, which make type II more expensive. Type I allows for up to 250 bar pressure, while type II allows for 450-800 bar. Today, the standard vessel capacity ranges from 7-75 kgH_2 up to 500 kgH_2 in modular configuration (Danish Energy Agency, 2020).

Type III and IV vessels are fully wrapped in a fiber resin composite, which makes them significantly lighter than type I and II vessels. Furthermore, the liner in the type III and IV acts as a hydrogen permeation barrier. For type III vessels the liner is a metallic liner, while type IV utilizes a polymer liner. The operating pressure of type III vessels are about 350-450 bar, while type IV can handle up to 1000 bar (Danish Energy Agency, 2020). A summary of the different types of hydrogen pressure vessels are presented in Table 5.

Table 5. Characteristics of different types of pressure vessels for hydrogen storage.

Type	Material	Storage pressure (bar)	Cost[a] (€/kg)	Gravimetric storage capacity (wt-%)[b]
Type I	Seamless steel or aluminium	< 250	500	1.00
Type II	Seamless steel or aluminium with partial composite wrapping	450-930	900	0.95 – 1.05
Type III	Fully wrapped composite pressure vessel with metallic liner	300-700	1 100	5.5
Type IV	Fully wrapped composite pressure vessel with polymer liner	350-1000	1 200	5.2

a) Cost from Danish Energy Agency, 2020.
b) Storage capacity from Langmi et al., 2022.

Pipelines

A promising option for large-scale storage of hydrogen is pipe storage. Using natural gas pipe storage as reference, approximately 12t of hydrogen per km of pipeline could be stored (Andersson et al., 2019). Hydrogen is produced at around 20-30 bar and can be stored in pipelines at a pressure around 100 bar. Pipeline large-scale storage is already a mature technology, and the main obstacle is related to the fact that hydrogen is more challenging to store than other gases due to its low density and hydrogen embrittlement (Khan et al., 2021). The safety risks associated with storing hydrogen is also larger than storing methane due to hydrogens large flammability range in air, the invisible flame and that it only requires a small amount of energy for ignition.

The energy required to compress hydrogen to storage pressure is about 3% (1 kWh/kgH_2) of the energy content of hydrogen (Sweco, 2022). Due to the relative low compression work required, pipeline storage is an energy efficient method compared to other hydrogen storage technologies. However, a hydrogen pipeline would only contain 88.4% of the energy content compared to if a pipeline with the same size was used to store methane (Khan et al., 2021). This is related to the difference in volumetric energy density of methane (35.5 MJ/m3) and hydrogen (10.78 MJ/m3). Since the volumetric energy density of hydrogen is lower, the implication is that the transport velocity through the pipeline has to be higher for hydrogen (about 3.29 times higher). However, due to restrictions of typical transmission pipelines, it is not possible to reach the velocity required to make it as energy efficient as if methane was stored.

Pipeline storage can either be realised by repurposing existing gas pipeline or construct new pipelines (Brown et al., 2011). Another alternative is direct hydrogen injection into the gas grid (HIGG). Approximate costs of repurposing an existing pipeline are 0.05 EUR/kgH_2, while a new H_2 pipeline would cost about 0.9 EUR/kgH_2 (International institute for sustainable analysis and strategies, 2022). Direct injection of up to 20 vol-% H_2 into the grid could be possible. However, in order to not lower the quality of the end-product, the hydrogen has to be separated from the methane at the end user. The separation adds an additional cost of 1.8-3.6 EUR/kgH_2 (International institute for sustainable analysis and strategies, 2022). Hydrogen could also be converted into methane to be compatible with existing gas grid. This adds an extra cost of about 0.9-1.8 EUR/kgH_2. In order to keep the pressure in the pipeline, compressor stations are necessary every 100-500 km of pipeline. For large-scale transport of 100-1000 tH_2/day the cost is < 1 EUR/kgH_2 (Khan et al., 2021).

Lined rock caverns

For large-scale storage of hydrogen (more than a few tonnes) underground geological storage is a safer and more economical alternative. There are different possible alternatives of underground storage, some of which are salt caverns, rock caverns, aquifers or depleted gas fields depending on geographical conditions (Lord et al., 2014). However, in a Swedish context the geological conditions limit the alternatives resulting in that only storage in rock caverns is possible (Johansson et al., 2018).

Storage in rock caverns can be constructed by excavating underground rock formations to form vertical cylindrical cavities with spherical tops and bottoms (Johansson, 2003). Rock cavern storage can either be lined or unlined. However, unlined caverns need to be constructed several hundred meters below ground (700-1 500 m) due to that the ground water pressure needs to be higher than the critical gas pressure. This type of technologies results in high capital costs and requires large storage volumes to be economically feasible (Johansson, 2003). The alternative is lined rock caverns (LRC) where an impermeable liner is applied around the cavern's boundaries. This results in storages with a possible operating pressure of 150-300 bar at depths of only 100-200 m (Johansson, 2003). For LRC storage a compressor station that controls the in and out flow from the caverns is required. The capital cost for a 500 tonne storage at 150-300 bar has been estimated to about 59-75 EUR2023/kgH_2 (Papadias et al., 2021). The cost includes underground costs such as cavern, tunnel, concrete and liner, as well as above ground costs such as piping, instrumentation and compressors.

3.1.3.2 Storage of Ammonia

The technologies relating to storage and transport of ammonia are mature technologies with standard and requirements for its handling in place. Ammonia has a high toxicity, which requires that anyone involved in handling it needs professional training (International Energy Agency, 2019).

There are two main storage solutions for ammonia: high pressure storage at about 990 bar and ambient temperature; or low-temperature storage at -33 °C and atmospheric pressure (Aziz et al., 2020). Ammonia can be stored underground (with a capacity up to 300 GWh) but is mainly stored in steel vessels (Patonia et al., 2020). High pressure storage in pressurized tanks is used up to 1 500 tons, while low-temperature storage in insulated tanks is used for larger volumes (up to 50 000 tons) (Klerke et al., 2008). The cost of storage of ammonia in refrigerated tanks are 0.59-1.12 EUR/kgNH_3 (Nayak-Luke et al., 2021). This is equivalent of about 3.33-6.30 EUR/kgH_2, making it a much more cost-efficient way of storage than hydrogen storage. Ammonia can either be used direct or decomposed (cracking) so that the hydrogen can be utilized. From an energy efficiency perspective, direct utilization is preferred.

Advantages related to storage of ammonia is its large-scale storage capacity, that it is a well-established mature technology with regulations and standard in place. Compared to liquid hydrogen storage, the cost of ammonia storage is low while the volumetric energy density (12.7 MJ/l) is high in comparison to hydrogen (8 MJ/l). Furthermore, it is less flammable than hydrogen and due to its lower volatility, compared to hydrogen, less advanced designs of storage tanks are needed.

3.1.3.3 Storage of Methanol

Due to being liquid at normal conditions, methanol can be stored in tanks comparable to conventional fuel oil tanks (Hammer et al., 2023). The relatively low volatility in atmospheric conditions (boiling point of 65°C) makes the risks related to the boiling point low (Stenersen et al., 2023). Methanol is typically stored in atmospheric tanks at ambient temperature. The volumetric energy density of methanol is significantly higher than for hydrogen (15.5 MJ/l compared to 8.6 MJ/l liquid hydrogen at below -253°C or 2.8 MJ/l for compressed hydrogen at 350 bar). Therefore, a ship's service range can be significantly longer when using methanol compared to hydrogen.

3.1.4 Environmental aspects

The environmental performance of marine fuels and their use can be investigated through several different frameworks. A common method used is life cycle assessment, LCA (Brynolf et al., 2023). The method aims to assess not only what happens when we directly use a product or technology, but also how the environment is impacted by the production of the raw materials required, production steps, recycling, or end-of-life treatment etc. LCA relies on systemic investigation of all energy and material components needed for a product to assess the environmental effects of the products use (Vigon et al., 1993). It is important to notice that LCA publications of marine fuels generally have different system boundaries, including technical, geographical, and time aspects, for example, which part of the life cycle is included, which impact categories and emissions are covered, and how it has been represented e.g., if first-of-a kind or more established production is assumed, etc. This could influence the possibility to compare the results (Malmgren, 2023). One important assumption is if a tank-to-wake/propeller (direct emissions from fuel use in vehicles), well-to-tank (emissions from up-stream activities), or well-to-wake/propeller (entire chain including up-stream and emission from fuels) perspective is considered.

LCAs of the environmental performance of marine fuels have been conducted for a range of different alternative fuels, including biofuels, hydrogen, ammonia, blue fuels (produced from natural gas with carbon capture and storage), and other electrofuels/power-to-X fuels and electricity in the literature (for a recent overview, see Brynolf et al., 2023). A few assessments for alternative abatement technologies such as onboard carbon capture are also available (Malmgren, 2023). Biofuel options assessed include biodiesel (Rapeseed methyl ester (RME), Hydrotreated vegetable oil (HVO), etc.), biogas, dimethyl ether (DME), ethanol, methanol (BIO-MeOH), Fischer-Tropsch (FT) diesel, and liquefied biogas (LBG). Electricity, hydrogen (H_2), ammonia (NH_3), and electrofuels (such as electro-methanol (e-MEOH), electro-LNG (e-LNG), electro-ammonia (e-NH_3), and electro-diesel) have also been assessed for specific use scenarios and production scenarios. The most common environmental issues investigated in the literature is climate change, which is influenced by the emissions of CO_2 and other GHG emissions (Brynolf et al., 2023). The second most common environmental impacts assessed are acidification and eutrophication, and the most common emissions besides GHGs include nitrogen oxides (NO_X), sulfur oxides (SO_X), and particulate matter (PM).

The range of assessments makes it possible to draw some general conclusion on the environmental performance of different alternative marine fuels, but the specific environmental performance must be assessed for a specific use scenario. How large the environmental impacts are from using a fuel depends both on fuel and engine characteristics, but also on the vessel type and the ships operational pattern (Kanchiralla et al., 2023). The climate change impact is directly dependent on the overall energy efficiency of the life cycle and the GHG intensity of the fuel production pathway, as well as the ship lifespan, component utilization, and other factors. Higher efficiencies result in less fuel being combusted and thereby reduced the emission of carbon into the atmosphere.

Below we present the results from a recent LCA of marine fuels (Brynolf et al., 2023) using a well-to-wake perspective (including fuel production, onboard fuel use, and construction of propulsion system), focusing on fuels for ships operated during 2030 with an outlook to 2050 and having a Nordic perspective (e.g., assuming Nordic electricity mix and fuel production conditions (e.g., distribution distances etc.). The assessed fuels include hydrogen, ammonia, and methanol, as well as methane, electricity in batteries, MGO and LNG for comparison. In Figure 7 the estimated lifecycle climate impact of a range of different marine fuel in a 2030 perspective expressed in global warming potential in a 100-year perspective (GWP100) is presented. The results reflect the average GWP100 results from using the fuel in a 2-stroke, 4-stroke, or fuel cell engine system.

The black dots in Figure 7 represent the total climate impact from well-to-wake while the blue (blue fuels), yellow (electrofuels) and green (biofuels) bars illustrate the contribution from fuel production (including transport and distribution) and grey bars ship operation. The negative climate impact from the production phase of the green fuels that contain carbon comes from that carbon is captured in this phase, either through carbon capture systems or biomass cultivation (see Malmgren (2023) for detailed explanation). The error bars show the distribution of the environmental impact between different engine systems (including 4-stroke (4S), 2-stroke (2S), and fuel cells (FC)). In Figure 7, NGccs represent steam reforming of natural gas with carbon capture and storage, NH_3 - ammonia, e-NH_3 – electro-ammonia, e-MEOH – electro-methanol, bio-MEOH – biomass-based methanol, e-LMG – electro-methane, , Elec-BE – Battery Electric, MGO – marine gas oil and LNG – liquefied natural gas.

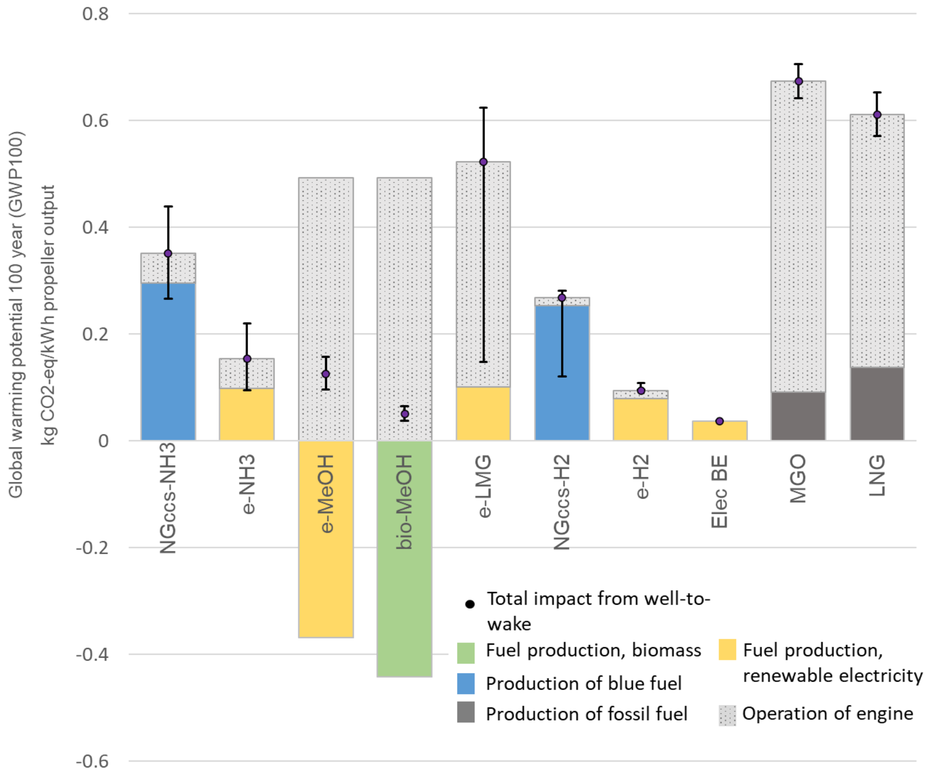


Figure 7. Life cycle climate impact for eight alternative marine fuels in 2030 compared to two fossil fuel alternatives (in a 100-year time perspective) as estimated in Brynolf et al. (2023). The error bars indicate the influence of engine choice on the overall results, and include 2-stroke, 4-stroke, and fuel cell propulsion.

All the assessed alternative fuel options could reduce GHG emissions by 2030 compared to traditional fossil fuels. For ammonia and hydrogen pathways, fuel production contributes, as expected, to the dominating share of the climate change impact. The biomass-based methanol options and battery electric options show the lowest climate impact, followed by the different green hydrogen options and green ammonia in fuel cells (represented by the lowest point on the error bars). Methane-based fuels are associated with leakage of methane (CH_4) during production, distribution, and use in marine engines which contribute significantly to the climate impact (Malmgren, 2023). The leakages can hopefully be reduced further through future regulations (Brynolf et al., 2023). Ammonia-based propulsion systems have challenges with emissions of nitrous oxides (N_2O) when used in marine engines; emissions that are still largely unknown. The future climate change performance of ammonia as a fuel is therefore currently unknown.

The assessment for 2030 is likely not representative for the climate change impacts of the fuel options in a longer time perspective, as the energy system and the technologies are under rapid development. The climate impact of the renewable (green) marine fuel and propulsion pathways assessed by Brynolf et al (2023) in 2050 perspective is presented in Figure 8 (black dots represent total climate impact from well-to-wake in this figure too). The 2050 perspective differs from the 2030 and include for example a less GHG intensive electricity mix, reduced impact from production of materials, the use of solid oxide electrolyzers for hydrogen production (instead of alkaline electrolyzers), the use of renewable urea and lower emissions of N_2O and CH_4 for the ammonia and methane cases.

In a 2050 perspective it seems possible to drastically reduce the GHG emissions from all the studied renewable marine fuel pathways. This is primarily due to the increased system efficiencies, energy production with a higher degree of renewable energy power and expected reductions in engine emissions (primarily N_2O and CH_4). The possibility to reduce engine emissions further are shown as a specific case for ammonia and methane use (represented by a '-' in Figure 8). The engine emissions of CH_4 and N_2O are strongly tied to the operational pattern, were operation on lower loads lead to higher emissions (Balcombe et al., 2022; Brynolf et al., 2023; Faber et al., 2020; Grönholm et al., 2021; Sommer et al., 2019). In Figure 8, ICE represents internal combustion engine, SOFC - solid oxide fuel cell, PEMFC – Proton-exchange membrane fuel cell, CH_2 – compressed hydrogen, and LH_2 – liquefied hydrogen.

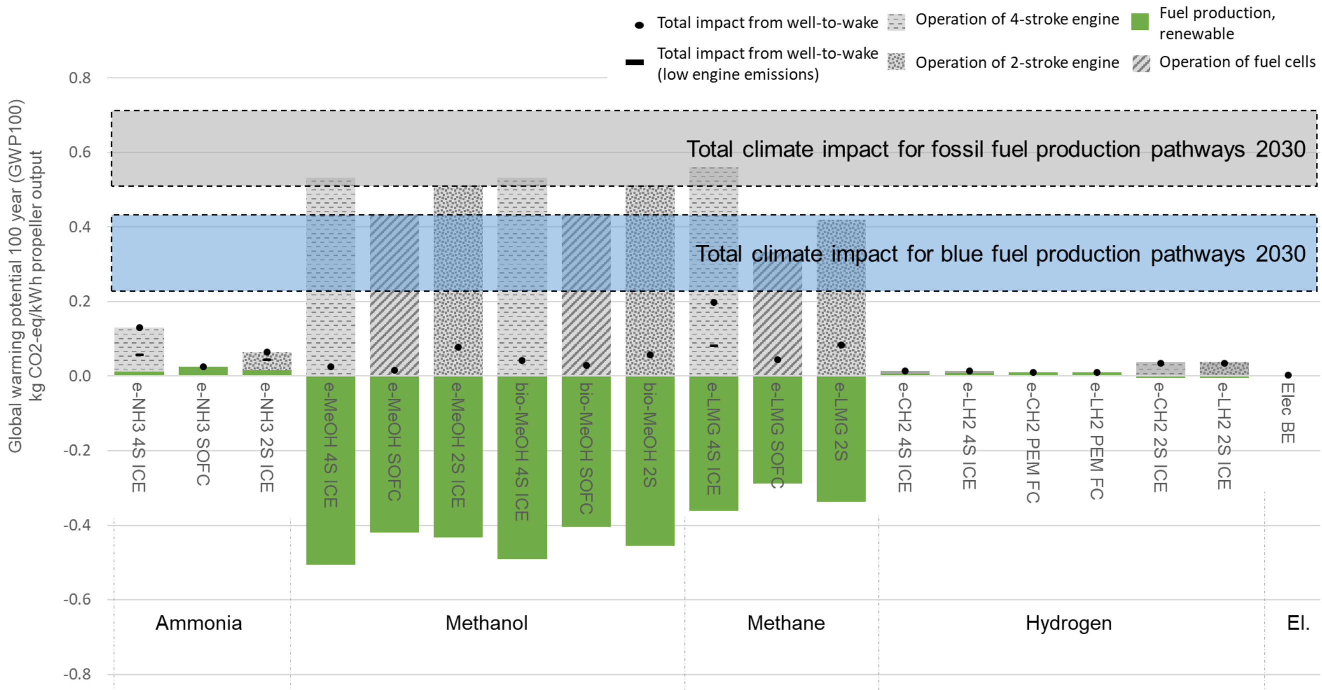


Figure 8. Life cycle climate impact for a range of renewable marine fuels and propulsion options in a 2050 perspective (in a 100-year time perspective) as estimated by Brynolf et al. (2023), compared to climate impact for some fossil fuels and blue fuel production pathways in 2030.

For other environmental impacts, a shift to alternative marine fuels (from conventional marine gas oil, MGO) is indicated to reduce some additional environmental impacts besides climate change (including e.g., acidification and particulate matter formation). This is due to combustion characteristics which include less emissions of particles and a lower content of sulphur in the green fuels. Fossil fuels contain trace elements of metals and other impurities, as well as sulphur. Various purification steps can reduce these contaminants, as is for example done to create low sulphur content fuel oils. However, any trace elements in the fuel will be released during combustion if the flue gas is not cleaned. Biofuels and electrofuels also have potential impurities from feedstock and process steps, but the amounts currently identified are lower than for fossil fuels (Faber et al., 2020; Malmgren, 2023). Despite these lower impacts on acidification and particulate matter, Brynolf et al. (2023) identifies that some of the alternative fuel options could potentially have higher impact on eutrophication, human toxicity, resource use, land use, and ionising radiation, compared with MGO. This trade-off is in line with literature using LCA to assess fuel choices in other sectors (Deutz et al., 2018; Grahn et al., 2022).

Environmental issues often associated with biofuels are high land use requirements, competition with food cultivation, and biodiversity impacts (Jeswani et al., 2020). The feedstock and cultivation practices are the main drivers of these impacts. Electrofuels have been less extensively researched but concerns regarding consequences of a large expansion of renewable energy, land use and water use has been raised (Malmgren, 2023). To secure a sustainable production of marine fuels therefore goes beyond their climate change impact and IMO's LCA guidelines (MEPC, 2023b) establishes water use, soil health, biodiversity conservation, and chemical use as key aspects to consider for production of sustainable marine fuels.

An alternative pathway to reduce or eliminate the emissions of pollutants, contaminants, or harmful substances from shipping activities is through abatement technologies (Andersson, 2016). Scrubbers is an abatement technology increasingly used to mitigate sulphur emissions from combustion of high-sulphur fuels and through this process met regulatory requirements. However, the use of scrubbers causes an increase in damaging emissions to water as the sulphur is released to water together with further contaminants (Lunde Hermansson et al., 2023). Using carbon capture as an abatement technology to mitigate climate change impacts has also been proposed and is increasingly investigated as a large-scale option (Malmgren, 2023). For onboard carbon capture systems to lead to lower climate change impacts, they must be combined with further utilization of carbon or carbon storage (Negri et al., 2023). The onboard carbon capture systems' environmental performance generally mitigates climate impacts if carbon losses throughout the system are low, and the additional energy required to reach the reduction target is not significant for the overall system performance (Malmgren, 2023). The benefits of such technologies are directly tied to the onboard system efficiency and lower system efficiency leads to higher impacts on all types of environmental issues.

3.1.5 Techno-economic assessment of production of renewable fuels

The main fuels evaluated in this report are methanol, hydrogen, and ammonia. A techno-economic assessment of the electrofuels were carried out and compared to literature data of the other fuels. This chapter presents the results of the techno-economic evaluation of e-methanol production, e-ammonia, and hydrogen from electrolysis. Each section includes the result of capital and operational costs, a cost/benefit analysis done by calculating levelized cost, as well as a sensitivity analysis and a comparison to the fossil equivalent of the fuel. In the end of the chapter, the levelized cost of the evaluated electrofuels are compared to the other possible marine fuels. The prices of raw material, energy and co-products used in the evaluation are presented in Table 6.

Table 6. Price of electricity, raw material and auxiliary material used in techno-economic assessment.

	Unit	Value	Source
Electricity[a]	50.01	EUR/MWh	Vattenfall, 2023
Demineralized H_2O	0.16	EUR/m^3	Pratschner et al., 2023
Steam	18.25	EUR/MWh	Andersson et al., 2007
Monoethanolamine (MEA)	1761	EUR/t	Pratschner et al., 2023
CuO catalyst	42.2	EUR/kg	Pratschner et al., 2023
Waste water	1.52	EUR/m^3	Pratschner et al., 2023
Oxygen	81	EUR/t	Pratschner et al., 2023
District heating[b]	23.5	EURMWh	Carlsson J., 2024

a) Electricity price is based on an average of the electricity price in northern Sweden 2023.
b) Average price of a range of price of district heating provided through communication via email.

Data and assumptions used for the cost/benefit analysis are presented in Table 7.

Table 7. Data and assumptions used in the cost/benefit analysis of the different fuel production technologies.

	Unit	Value	Source
Plant lifetime	25	years	Assumption
Lifetime of electrolyzer stack	11	years	Pratschner et al., 2023
Cost of replacing electrolyzer stack	50	% of electrolyzer stack capital cost	Parra et al., 2023
Nominal discount rate	10	%	Assumption
Annual inflation rate	2	%	Regeringskansliet, 2023
Real discount rate	8	%	Calculated
Price increase per year	2	%	Assumption

Production cost and CO_2-emissions of the fossil equivalent to the marine electrofuels that were evaluated are presented in Table 8.

Table 8. Cost of production and CO_2-emission from production of the fossil equivalents of the evaluated marine electrofuels.

Fuel	Cost of production [EUR/t]	CO_2-emissions [tCO_2/t]	Source
Methanol	269	3.42	Arnaiz del Pozo et al., 2022; Methanol Institute, 2022
Hydrogen	5500	10.5	Hydrogen Europe, 2023
Ammonia	400	2.4	International Energy Agency, 2021; Guidehouse, 2023

3.1.5.1 e-Methanol

Power-to-liquid is a concept where hydrocarbons are produced by combining hydrogen, from electrolyzer using renewable electricity, and CO_2. Example of this type of process is Liquid Wind's process where biogen CO_2 is reacted with hydrogen from electrolysis to produce e-methanol (Liquid Wind, 2022).

The general power-to-methanol process consists of the following main process steps: a carbon capture unit to separate the CO_2 from the flue gas stream, an electrolyzer and a methanol synthesis plant (Pratschner et al., 2023). In present work the monoethanolamine (MEA) based carbon capture technology has been selected, with a capture efficiency of 90% (Brandl et al., 2021). The hydrogen is produced from an PEM electrolyzer with an efficiency of 75% (Parro et al., 2023), followed by a methanol synthesis plant. The operational hours per year is assumed to be 8 000 hours. It is assumed that the heat and power plant from where the CO_2 is captured already is in place and requires retrofitting to accommodate the power-to-methanol process. The cost for retrofitting is accounted for by multiplying the investment cost of the power-to-methanol plant with a retrofit difficulty factor (RDF) of 9% (Schmitt et al., 2023). The upper range of RDF was selected.

Capex and Opex

For the evaluation of the production cost of e-methanol, a plant with a production capacity of 130 000 t/year has been used. This corresponds to the capacity of Liquid Wind's planned production facility of e-fuels in Umeå, Sweden (Liquid Wind, 2023). The raw material and energy in- and outputs to the plant were scaled based on Liquid Wind's production facility in Örnsköldsvik with a production capacity of 50 000 t MeOH/year (Liquid Wind, 2022; Liquid Wind and Övik Energi, 2022). Liquid Wind's plant was used as reference to ensure that the calculations were based on up-to-date values and capacities. The resulting material flows are presented in Table 9.

Table 9. In- and outputs from the power-to-methanol process with a yearly production capacity of 130 kt MeOH.

	Unit	Value	Source
Output			
Production capacity	t/year	130 000	
Electricity	MWh/tMeOH	8.9	Liquid Wind and Övik Energi, 2022
Waste heat	MWh/tMeOH	7.6	Liquid Wind and Övik Energi, 2022
Wastewater	m^3/tMeOH	0.56	Pratschner et al., 2023
Input/intermediate			
Bio-CO_2 input	t/tMeOH	1.4	Liquid Wind and Övik Energi, 2022
Demineralized H_2O	m^3/tMeOH	1.61	Pratschner et al., 2023
Steam	MWh/tMeOH	2.8	Pratschner et al., 2023
Monoethanolamine (MEA)	kg/tMeOH	4.2	Pratschner et al., 2023
CuO-catalyst	kg/tMeOH	0.03	Pratschner et al., 2023
Hydrogen (intermediate)	t/tMeOH	0.2	Liquid Wind and Övik Energi, 2022

Investment costs of process equipment were scaled according to Equation (2) based on the values presented in Table 9, using the m factors presented in Table 10.

Table 10. Scaling exponent used for different process sections of the power-to-methanol plant.

Process section	m	Source
Carbon capture unit (MEA)	0.65	Pratschner et al., 2023
Methanol synthesis	0.80	Pratschner et al., 2023
PEM electrolyzer[a,b]	1	Reksten et al., 2022
Grid connection	0.90	Pratschner et al., 2023

a) Capital cost is calculated and scaled linearly based on specific capital cost (1305 EUR/kW).
b) Balance of plant is included in the cost.

The total fixed capital investment of the different process units was based on values from the work of Pratschner et al. (2023) and scaled to appropriate size. The resulting equipment costs are presented in Figure 9.

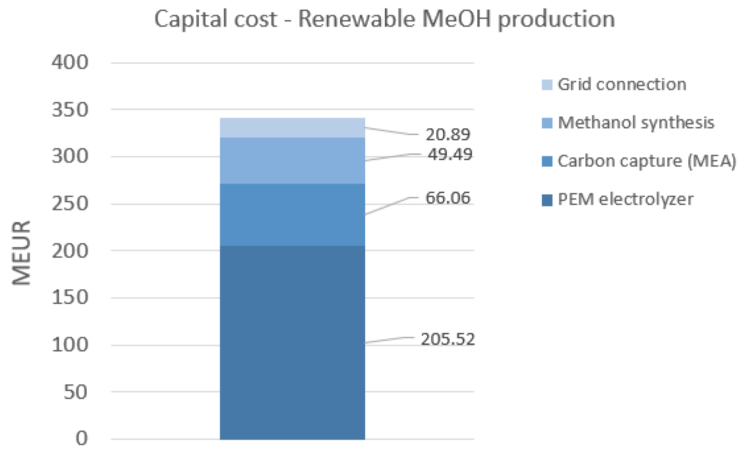


Figure 9. Equipment cost for the major process sections of the power-to-methanol plant. The values are the total fixed capital investment, calculated using a lang factor of 5.04.

The fixed operating costs were calculated according to the methodology presented in *Chapter 2.4.3 Methodology for techno-economic assessment,* while the variable operating costs were calculated based on material and energy flows and cost data. The material and energy flows required were linearly scaled based on values from Pratschner et al. (2023). The prices of electricity and raw materials used in this evaluation are presented in Table 6. The resulting operational costs are presented in Figure 10. Where the variable cost, excluding electricity, constitutes a minor part of the total operational cost.

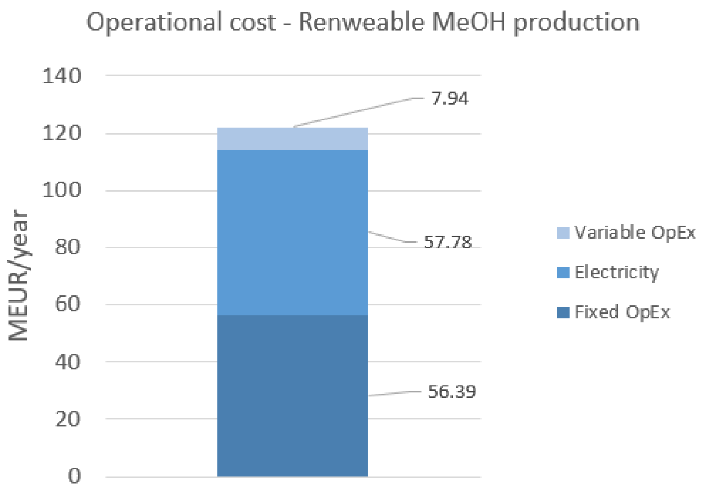


Figure 10. Operational cost for the power-to-methanol production divided in fixed and variable costs, as well as cost for electricity.

Cost/Benefit analysis

The cost/benefit analysis was performed using the method presented in *Chapter 2.4.3 Methodology for techno-economic assessment*. The levelized cost of methanol was calculated based on the assumptions presented in Table 7. As described in the methodology, the investment was assumed to be split into three years. Production is assumed to start year 3 and reach full capacity year 5. The fixed operating costs are assumed to be 100% from production start, while the variable operating costs increase with the same rate as the production. Furthermore, the process produces oxygen and waste heat that can be sold as district heating. The cost build-up of the production of e-methanol is presented in Figure 11, with a resulting levelized cost of e-methanol of 1009 EUR/tMeOH.

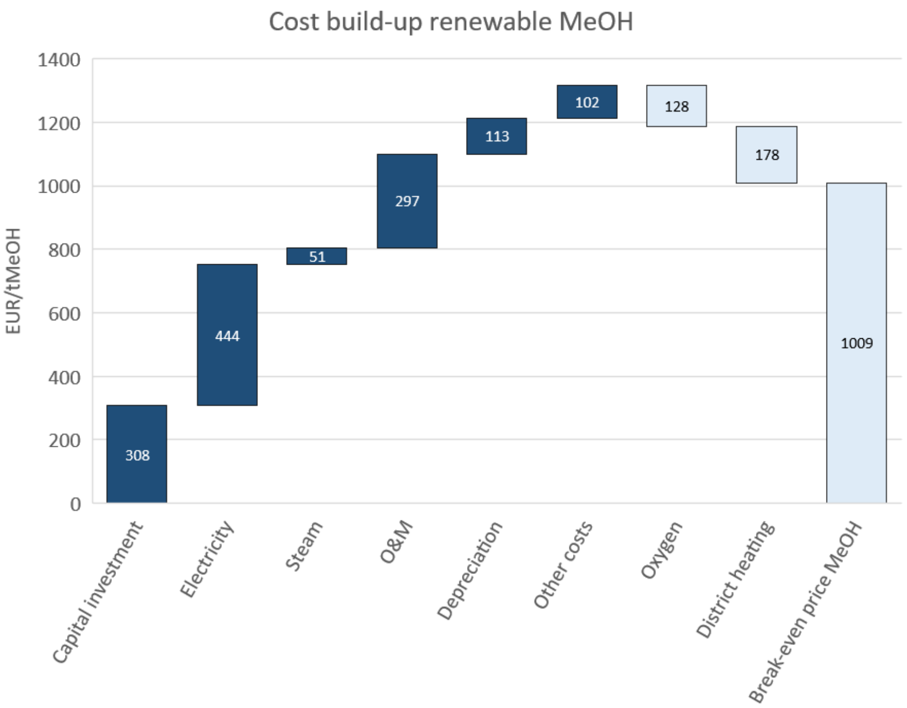


Figure 11. Cost build-up for the production of e-methanol.

As can be seen, the major cost contributing to the price of methanol is the cost of electricity. Furthermore, the operation and maintenance (O&M), as well as the capital investment, constitutes significant parts of the cost. The cost was compared to the cost of production of fossil methanol from steam methane reforming. It is assumed that the cost to produce fossil methanol is 269 EUR/t (Arnaiz del Pozo et al., 2022) and that 3.42 tCO_2/tMeOH is emitted during production (Methanol Institute, 2022). The resulting CO_2-price required for e-methanol to be cost-competitive would therefore be 227 EUR/tCO_2. This can be compared to the current ETS price of 80 EUR/tCO_2 (Swedish Energy Agency, 2023a). However, the ETS price may rise significantly in the future.

A sensitivity analysis was carried out where one parameter at a time was changed in order to capture the impact of electricity price, interest rate and total fixed capital cost on the levelized cost, as well as the required CO_2-price to make the production economically feasible. The sensitivity analysis is presented in Figure 12.

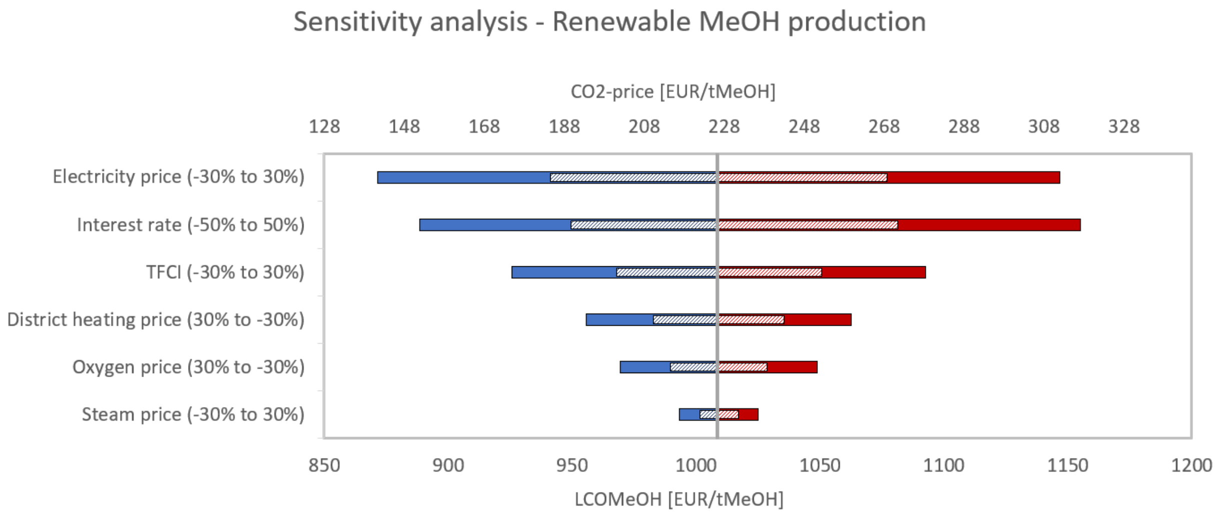


Figure 12. Single parameter sensitivity analysis of levelized cost of renewable methanol (solid bars, bottom axis) and CO_2-price required for renewable methanol production to be economically feasible (dashed bars, top axis).

As can be seen, the electricity price has the largest impact on the levelized cost and CO_2-price. The sensitivity analysis indicate that the interest rate and electricity price have a more significant impact on the feasibility of e-methanol production than the total fixed capital investment. Additionally, the selling price of district heating shows a significant impact on the levelized cost of methanol production. The ETS price in the start of 2023 was about 100 EUR/tCO_2 and had decreased to about 80 EUR/tCO_2 by the end of the year (Swedish Energy Agency, 2023a). The sensitivity analysis indicated that a lower price for renewable electricity as well as a more optimized process, resulting in a lower total fixed capital investment, as well as an increased price for CO_2would be required to make the production of e-methanol economically feasible.

3.1.5.2 e-Hydrogen

Electrolysis of water, using renewable electricity, is a way of producing renewable hydrogen. The three main different types of electrolyzers are alkaline electrolyzer, proton exchange membrane (PEM) electrolyzer and solid oxide electrolyzer cell (SOEC) (Rizwan et al., 2021). By the three, the alkaline electrolyzer and the PEM electrolyzer are the two with highest technology readiness levels (TRL). In this evaluation the electrolyzer has been assumed to be an alkaline electrolyzer since this type of electrolyzer is a well-established technology. Except the electrolyzer unit, the renewable hydrogen production requires support systems so called balance of plant (BoP) (SynerHy, 2022). Balance of plant includes a power supply system, a demineralized water system, a hydrogen purification system, a lye preparation and recirculation system, heat exchanger, as well as safety system and gas analyzers.

Electrolyzer plants consists of several electrolyzer stacks with a stack size from 2 up to 20MWe size per stack (IRENA, 2020). In this work, an electrolyzer stack size of 10 MWe has been assumed. Furthermore, the size of the electrolyzer plant was selected so that the amount of hydrogen produced had an equivalent amount of energy as the methanol produced in the methanol case (i.e., 130 kta MeOH). Methanol has an energy density of 22 MJ/kg and hydrogen has an energy density of 120 MJ/kg, resulting in an annual production of 23.8 kt H_2. In order to produce 23.8 kta H_2 from an electrolyzer plant with an efficiency of 66%, 15 electrolyzer stacks are required, resulting in an electrolyzer plant capacity of 150 MWe.

Capex and Opex

Capital cost of alkaline electrolyzers with the minimum size of 10MWe scaled to 2023 value were estimated to 622 – 1243 EUR/kWhe (IRENA, 2020). This value includes the cost for the balance of plant (BoP). The average of 932.5 EUR/kWhe was selected, resulting in a fixed capital investment (FCI) of 140.3 MEUR.

The fixed operational costs were calculated based on the information in Table 1. The variable operating costs were calculated based on mass and energy flows. The electricity price and price of demineralized water used is the same as presented in Table 6. The amount of demineralized water was calculated based on the work of Saulnier et al. (2020) and the available amount of district heating was calculated based on the work of Jonsson et al. (2022). The resulting mass and energy flows are presented in Table 11, and the resulting operational costs are presented in Figure 13.

Table 11. In- and outputs from the electrolyzer plant with a yearly production capacity of 23.8 kt H_2.

	Value	**Unit**
Output		
Hydrogen production	23 522	t/year
Oxygen production	7.88	t/tH_2
District heating	14.32	MWh/tH_2
Input		
Electricity	50.65	MWh/tH_2
Demineralized water	11	m^3/tH_2

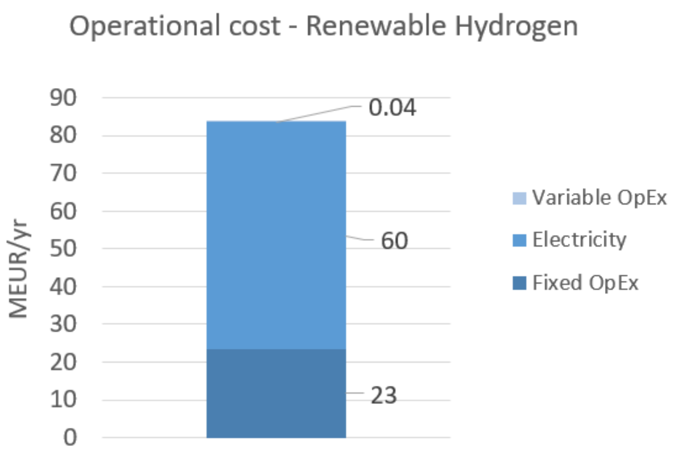


Figure 13. Operational cost for the renewable hydrogen production divided in fixed and variable costs, as well as cost for electricity.

As can be seen, the electricity constitutes a major part of the operational costs, while the fixed operational costs constitute about half of the cost of electricity.

Cost/Benefit analysis

The cost/benefit analysis was performed using the method presented in *Chapter 2.4.3 Methodology for techno-economic assessment*. The levelized cost of hydrogen was calculated based on the assumptions presented in Table 7. The investment was assumed to be split into three years. Year 1: 30% of investment; years 2: 60% of the investment; and year 3: 10% of the investment was paid. Production is assumed to start year 3 with 30% production, reach 75% production year 4 and full production year 5. The fixed operating costs are assumed to be 100% from production start, while the variable operating costs increase with the same rate as the production. Furthermore, the process produces oxygen and waste heat that can be sold as district heating. The cost build-up of the production of renewable hydrogen is presented in Figure 14. Showing a levelized cost of hydrogen of 3397 EUR/tH_2.

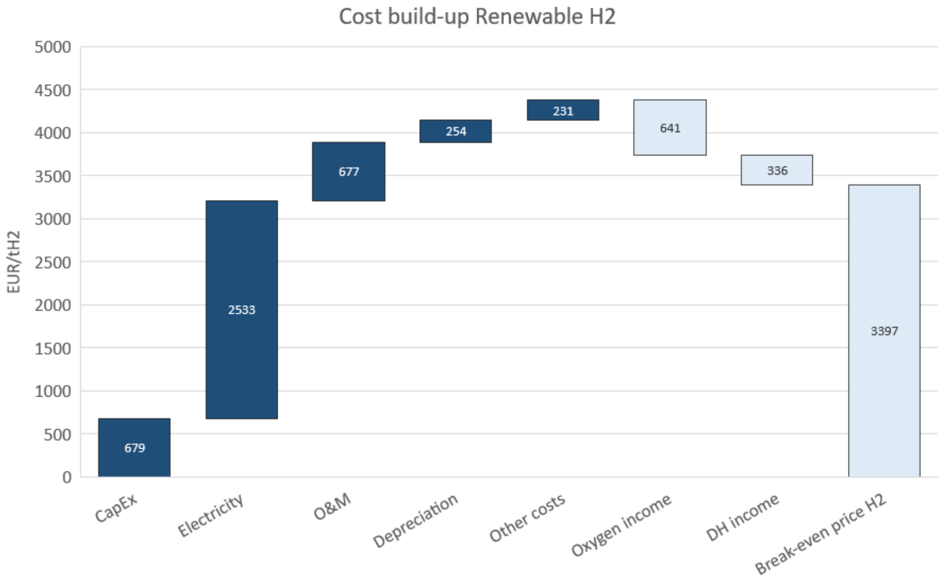


Figure 14. Cost build-up for the production of renewable hydrogen.

As could be expected, the major cost contributing to the price of hydrogen is the cost of electricity. The second and third largest contributors the cost build-up are the operation and maintenance (O&M), as well as the capital investment. The cost was compared to the cost of production of fossil hydrogen from steam methane reforming of natural gas. It is assumed that the cost to produce fossil hydrogen from SMR is 5500 EUR/tH_2 (assuming the production plant is already in place) and emits 10.5 kgCO_2/kgH_2 (Hydrogen Europe, 2023). Based on these values, the cost of producing hydrogen is higher than the cost of producing hydrogen through electrolysis. This is in large due to the high price of natural gas as a result of EU's sanctions against Russia following Russia's invasion of Ukraine. During 2020 the price of producing fossil hydrogen from SMR was about 1200 EUR/tH_2, compared to 5500 EUR/tH_2 2022 (Hydrogen Europe, 2023).

A sensitivity analysis was carried out where one parameter at a time was changed in order to capture the impact of electricity price, interest rate, oxygen price, total fixed capital cost and district heating selling price on the levelized cost. The sensitivity analysis is presented in Figure 15.

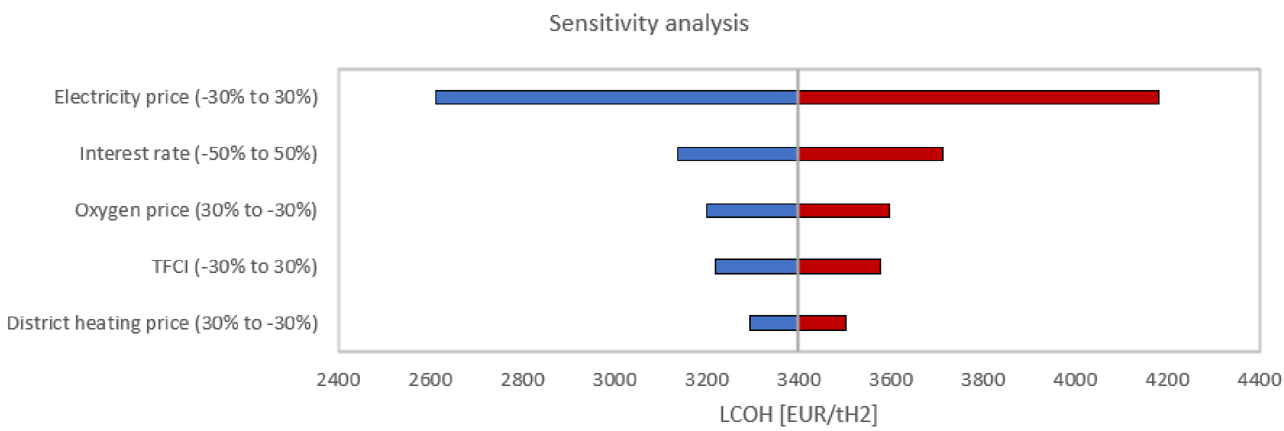


Figure 15. Single parameter sensitivity analysis of levelized cost of renewable hydrogen.

As can be seen, the electricity price has the largest impact on the levelized cost. The lowest impact is related to the district heating selling price, while the selling price of oxygen and the total fixed capital investment have similar impacts. The sensitivity analysis indicates that the interest rate and electricity price will have a more significant impact on the price of production of renewable hydrogen than optimization and reduced cost of the process equipment as well as the variation in the selling price of co-products.

3.1.5.3 e- Ammonia

Green ammonia can be synthesized through the Haber-Bosch process by letting hydrogen from electrolysis and nitrogen from an air separation unit (ASU) react (Campion N et al., 2023). The main process steps of a green ammonia production plant are the Haber-Bosch plant, a desalination unit, an electrolyzer plant and an air separation unit. In present work, the electrolyzer unit was assumed to be an alkaline electrolyzer with an efficiency of 66%.

Furthermore, the size of the green ammonia production plant was selected so that the amount of ammonia produced had an equivalent amount of energy as the methanol produced in the methanol case (i.e., 130 kt/year MeOH). Methanol has an energy density of 22 MJ/kg and ammonia has an energy density of 18.6 MJ/kg, resulting in an annual production of 153.8 kt/year ammonia. The operational hours per year is assumed to be 8 000 hours.

Capex and Opex

The cost estimations of the different process steps of a green ammonia plant were based on the work of Campion et al. (2023). Fixed capital investment for each process step for a green ammonia plant with the capacity 430 kt/year was used as a base and scaled using Equation 2 together with the capacities in Table 12 and to find the fixed capital investment (FCI) for a plant of size 153.8 kt/year.

Table 12. In- and outputs from the power-to-ammonia process with a yearly production capacity of 153.8 kta.

	Unit	Value	Source
Output			
Ammonia production capacity	t/year	153 763	
Oxygen production	t/tNH_3	1.47	Campion et al., 2023
District heating	MWh/tNH_3	1.34	Campion et al., 2023
Input/Intermediate			
Hydrogen (intermediate)	t/tNH_3	0.19	Campion et al., 2023
Electricity use	MWh/tNH_3	10.3	Campion et al., 2023
Demineralized water	m^3/tNH_3	2.71	Campion et al., 2023

The amount of produced ammonia was used as the capacity to scale the Haber-Bosch synthesis plant and the ASU and the amount of demineralized water was used to scale the desalination plant. The scaling exponents used to scale the process sections are presented in Table 13.

Table 13. Scaling exponent used for different process sections of the power-to-ammonia plant.

Process section	m	Source
Haber-Bosch + Air separation unit	0.5	Campion N et al., 2023
Alkaline electrolyzer[a,b]	1	Reksten et al., 2022
Desalination plant	0.6	Campion N et al., 2023
Short-term on-site hydrogen storage	0.6	Campion N et al., 2023

a) Capital cost is calculated and scaled linearly based on specific capital cost (932.5 EUR/kW).
b) Balance of plant is included in the cost.

The electrolyzer cost was calculated by using the same cost as was used for calculation of the capex of the alkaline electrolyzer presented in *Chapter 3.1.5.2 e-Hydrogen* with a cost of 932.5 EUR/kWhe. The resulting equipment costs are presented in Figure 16.

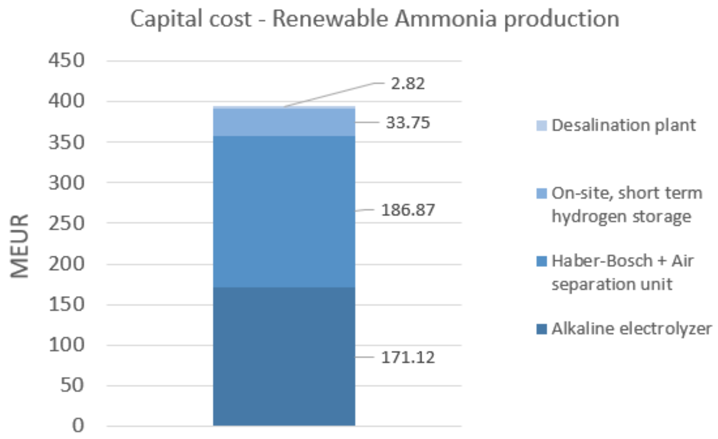


Figure 16. Equipment cost for the major process sections of the power-to-ammonia plant. The values are the total fixed capital investment, calculated using a lang factor of 5.04.

The fixed operating costs were calculated according to the methodology presented in Table 1, while the variable operating costs were calculated based on material and energy flows and cost data. The cost data used is presented in Table 6. The resulting operational costs are presented in Figure 17.

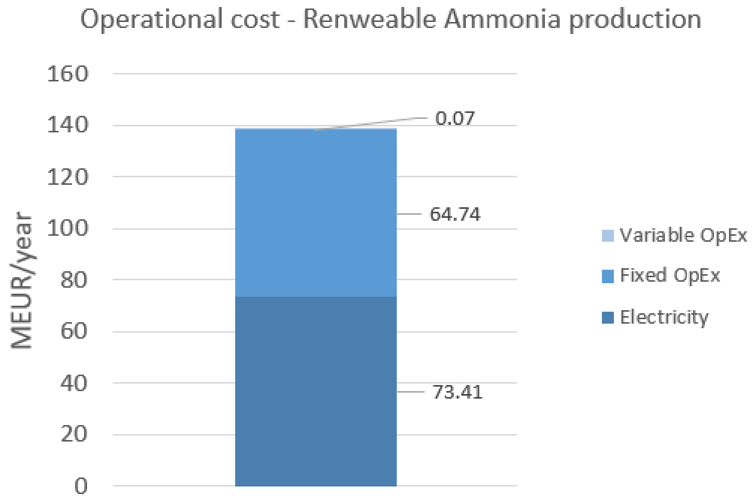


Figure 17. Operational cost for the power-to-ammonia production divided in fixed and variable costs, as well as cost for electricity.

Where the variable cost, excluding electricity, constitutes a minor part of the total operational cost.

Cost/Benefit analysis

The cost/benefit analysis was performed using the method presented in *Chapter 2.4.3 Methodology for techno-economic assessment*. The levelized cost of ammonia was calculated based on the assumptions presented in Table 9. The investment was assumed to be split into three years. Year 1: 30% of investment; years 2: 60% of the investment; and year 3: 10% of the investment was paid. Production is assumed to start year 3 with 30% production, reach 75% production year 4 and full production year 5. The fixed operating costs are assumed to be 100% from production start, while the variable operating costs increase with the same rate as the production. Furthermore, it is assumed that the process produces oxygen and district heating that can be sold. The cost build-up of the production of renewable hydrogen is presented in Figure 18. Showing a levelized cost of hydrogen of 884 EUR/tNH_3.

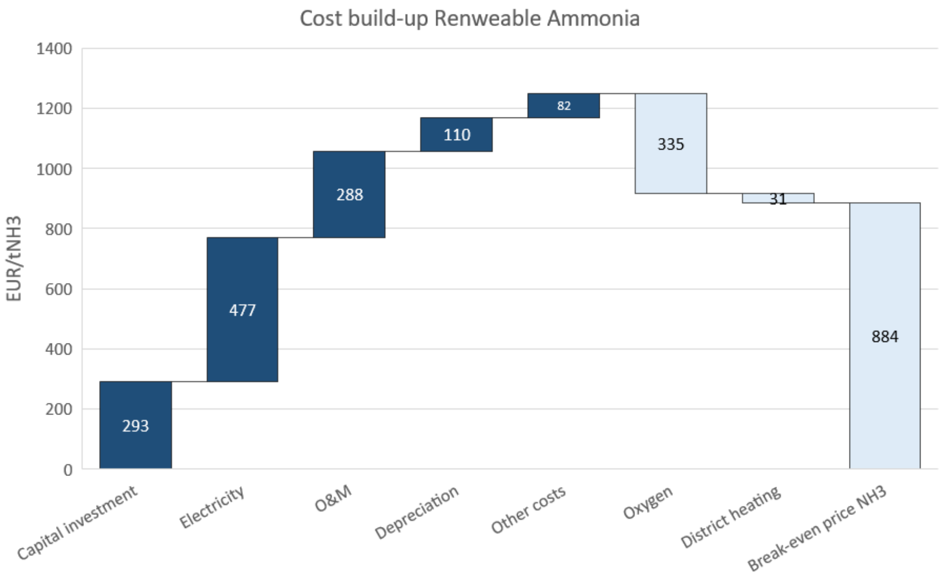


Figure 18.Cost build-up for the production of renewable ammonia.

The major cost contributing to the price of hydrogen is the cost of electricity. The second and third largest contributors the cost build-up are the fixed operational costs, as well as the capital investment. The cost was compared to the cost of production of fossil ammonia from steam methane reforming of natural gas. It is assumed that the cost to produce fossil ammonia from SMR is 400EUR/t and emits 2.4 kgCO_2/kg (International Energy Agency, 2021; Guidehouse, 2023). The resulting CO_2-price required for green ammonia to be cost-competitive is 201.5 EUR/tCO_2. This can be compared to the current ETS price of 80 EUR/tCO_2 (Swedish Energy Agency, 2023a).

A sensitivity analysis was done where one parameter at a time was changed in order to capture the impact of electricity price, interest rate, oxygen price, total fixed capital cost and district heating selling price on the levelized cost as well as the required CO_2-price to make the production economically feasible. The sensitivity analysis is presented in Figure 19.

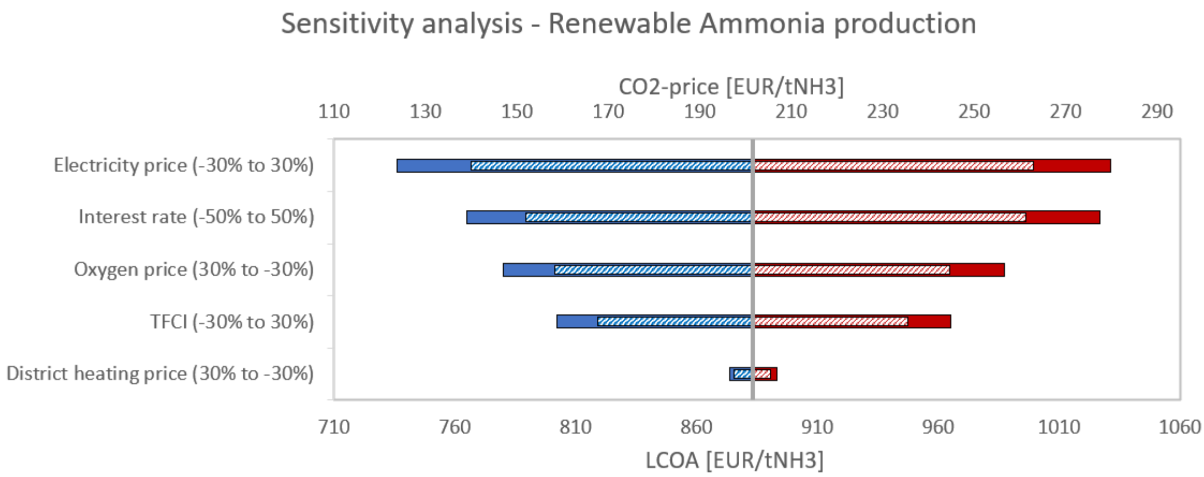


Figure 19. Single parameter sensitivity analysis of levelized cost of renewable ammonia (solid bars, bottom axis) and CO_2-price required for renewable ammonia production to be economically feasible (dashed bars, top axis).

As shown in figure, the electricity price and interest rate have a large impact on the levelized cost of ammonia and the required CO_2-price. The lowest impact is related to the price of district heating. The oxygen price and total fixed capital investment also significantly impacts the levelized cost and required CO_2-price. The sensitivity analysis indicates that interest rate and electricity price will have a more significant impact on the feasibility of green ammonia production than optimization of the process equipment. The result suggests that a lower price for renewable electricity as well as a more optimized process and an increased CO_2-price, would be necessary in order to make the production of e-ammonia economically feasible.

3.1.5.4 Summary of techno-economic assessment

Figure 20 shows the share of the operational cost that can be attributed to the cost of electricity for each fuel. The electricity demand for hydrogen production and methanol production is mainly related to electrolysis, while the ammonia production a large portion of the electricity demand is due to electrolysis but is also related to the air separation unit (ASU).

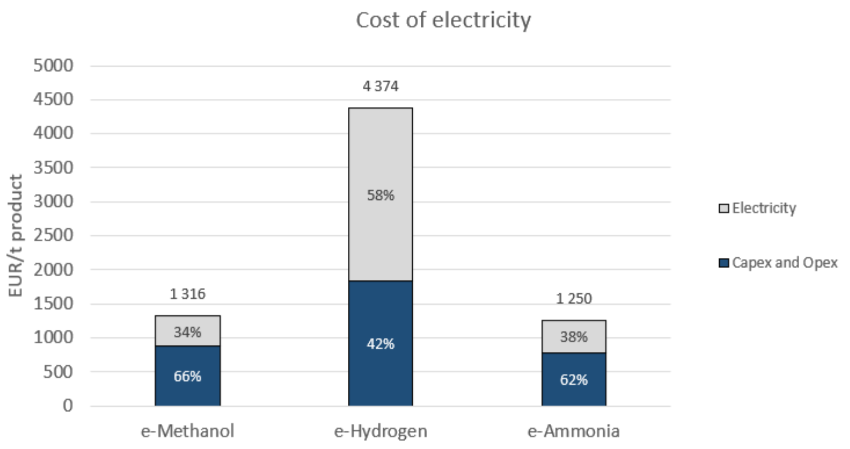


Figure 20. The graphs shows the share of the operational cost (not including income from co-products) of renewable methanol, hydrogen and ammonia that is related to the cost of electricity.

The three processes depend heavily on electrolyzers and renewable electricity. Optimization of electrolyzers and increased electrolyzer efficiency, as well as reduced renewable electricity price and increase CO_2-price are the key factors making these three production pathways of electrofuels economically feasible. Development of electrolyzers, and increased manufacturing capacity would, due to economics of scale, reduce the investment cost, the electricity demand and, as an effect, reduce the TFCI and cost of electricity required to produce these fuels. An increased CO_2-price would further incentivize the production of renewable fuels rather than the fossil counterpart. A comparison of the levelized cost of energy (LCOE) of the evaluated electrofuels with other alternative marine fuels are presented in Figure 21.

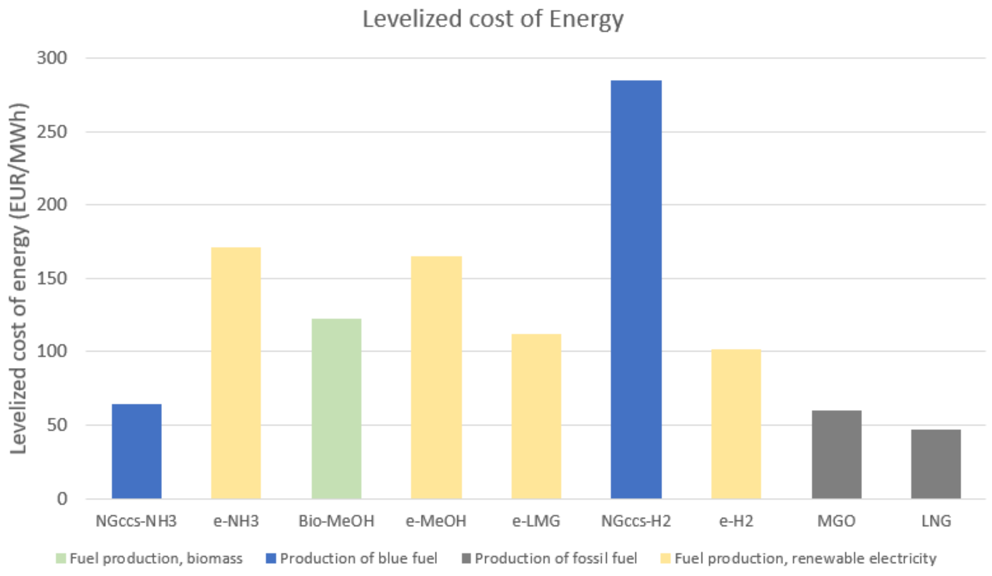


Figure 21. Comparison of e-fuel LCOE with cost of bio-fuel production, production of blue fuels (fossil with CCS) and fossil fuels.

The production cost of the other possible marine fuels used for comparison are also presented in Table 14.

Table 14. Levelized cost of production for alternative marine fuels.

Fuel	Cost of production [EUR/MWh]	Source
Bio methanol	123	Butera et al., 2021
Blue hydrogen	285	Hydrogen Europe, 2023
Blue Ammonia	64	Arnaiz del Pozo et al., 2022
e-LMG	112	Al-Breiki et al., 2023
MGO	60	Strantzali et al., 2023
LNG	47	Kotek et al., 2023

3.1.6 Economic aspects

When evaluating alternative marine fuels, the production, distribution, storage at port and bunkering are all of importance. The techno-economic assessment of the alternative marine fuels show that e-ammonia and e-methanol has a rather high levelized cost of energy, while e-hydrogen has a lower LCOE. However, none of the e-fuels has a LCOE close to that of the conventional marine fuels. Furthermore, bio-methanol and ammonia from blue hydrogen has a lower cost than their electrofuel counterpart. However, the blue hydrogen shows a much higher LCOE compared to the other alternatives. The blue ammonia shows a LCOE comparable with the conventional marine fuels.

3.1.6.1 Storage of alternative fuels

The literature review of the different storage solutions for the alternative fuels can be found in *Chapter 3.1.3 Infrastructure and storage needs*. A summary of the fuel storage solutions is presented here:

- Hydrogen can be stored in pressure vessels, pipelines and in lined rock caverns. The storage of hydrogen in pipelines can be used for distribution to port from producer, as well as large scale storage. Pressure vessels exist in different classes and is suitable for storage at port and onboard ships, while lined rock caverns could be suitable for large scale storage in connection to ports. All hydrogen storage technologies have in common that they are expensive due to complexity of storing hydrogen because of its physical properties.
- Ammonia storage can be divided into high pressure (990 bar) and low temperature storage (-33 °C). It can also be stored underground, but is mainly stored in steel vessels. Compared to hydrogen it is a more cost-efficient, well-established, and mature technology and has a large-scale storage capacity.

- Methanol is usually stored in atmospheric tanks comparable to conventional fuel oil tanks and there are well-established and mature technologies for the storage of this type of fuel.

3.1.6.2 Bunkering of alternative fuels

Bunkering can be categorized into four main types: ship-to-ship, terminal-to-ship, truck-to-ship and portable tank (Ellis et al., 2021). Methanol bunkering is done using all the methods and there is much knowledge, routines, and guidance for the safe transfer of methanol to ship and it has been carried out for several cases. Ammonia bunkering, similar to the alternative fuels such as LNG and LPG, can also be carried out in the four mentioned methods. The methods selected depends on the amount of ammonia bunkering required, operational circumstances, and time constraints (Duong et al., 2023):

- Ship-to-ship is suitable for medium to large ammonia vessels and is a fast method of bunkering. However, it requires a high investment and is affected by weather and sea conditions.
- Terminal-to-ship is a fast method that is available for all types of vessels, but mainly large ones. As for ship-to-ship, the downside is the required high investment cost.
- Truck-to-ship is a low investment cost alternative that is suitable for small vessels. However, it is a relatively slow method and not suitable for large vessels.
- Portable tanks have the advantage of if being a quick, flexible method. On the downside are high operation and maintenance costs and that the method is only suitable for small vessels.

Hydrogen bunkering method depends on how the hydrogen is being stored. If it is stored as a gas, the bunkering can be carried out through pressure balancing or compressing the gas into the ship (Hyde & Ellis, 2019). While if it is stored as liquid hydrogen, cryogenic pumps are needed to transfer the hydrogen from port to ship. The method of bunkering liquid hydrogen is similar to the method of bunkering LNG.

Pressure balancing requires that the hydrogen is stored at higher pressure in the port than the storage pressure on the ship (Hyde & Ellis, 2019). For example, a ship storing hydrogen at 350 bar would require a storage pressure of 500 bar at port. The method does not require any compressor. However, since a ship only could be filled from a storage until the storage pressure reaches the same pressure as the ship's storage pressure, a large portion of the stored hydrogen is inaccessible. This method therefore requires large storage space at the port.

Compressing hydrogen gas into a ship involves using a compressor to transfer hydrogen from lower pressure (usually about 20 bar) to the ship. When compressing hydrogen through adiabatic compression, heat is released that can soften the tanks of the vessels (Hyde & Ellis, 2019). This in turn can lead to failure of the pressure vessels. It is therefore important to carefully control the flow rate of hydrogen while bunkering through compression.

3.1.6.3 Qualitative assessment of production, storage, bunkering and use of alternative fuels

A summary of the assessment of the relative investments required for the production, storage, bunkering and use of alternative marine fuels is presented in Table 15. The result is a summary of the literature review of the alternative fuel technologies and storage solutions, as well as the techno-economic assessments presented throughout *Chapter 3.1 Description of alternative fuels and charging facilities.*

Table 15. Level of investment required for production, storage, bunkering and use of alternative marine fuels. Green indicates a relatively low investment, yellow indicates intermediate, and red indicates a relatively high investment cost.

	Production	Storage	Bunkering	Use
e-H_2	(green)	(red)	(red)	(yellow)
e-NH_3	(red)	(yellow)	(yellow)	(yellow)
e-MeOH	(red)	(green)	(green)	(green)
NGccs-H_2	(red)	(red)	(red)	(yellow)
NGccs-NH_3	(green)	(yellow)	(yellow)	(yellow)
Bio-MeOH	(yellow)	(green)	(green)	(green)
e-LMG	(green)	(green)	(green)	(green)

As can be seen, e-hydrogen (e-H_2) has a relatively low production cost compared to the other alternatives. While hydrogen from steam reforming of natural gas with carbon capture (NGccs-H_2) has a high investment cost. Furthermore, the storage and bunkering of hydrogen requires high investment costs due to the physical properties of hydrogen, which results in expensive and large equipment and storage relative to the energy content of the fuel. The TRL of engines and fuel-cells for hydrogen is relatively low and would most likely require higher investment costs then what is required for the use of methanol or the more conventional fuels.

Ammonia from steam reforming combined with carbon capture and storage, CCS (NGccs-NH_3) has a relatively low investment cost, while the e-ammonia (e-NH_3) has a high investment cost. With respect to storage and bunkering, ammonia is more cost-efficient in comparison to hydrogen (Duong et al., 2023). This is partially due to well-established and mature technology surrounding the handling of ammonia, but also as a result of the higher volumetric energy density compared to hydrogen. However, due to the safety risks and more severe storage conditions of ammonia in comparison to methanol, the bunkering of ammonia would most likely require higher investment costs than methanol regardless of it being a well-established technology. The TRL for the use of ammonia is relatively low and would most likely require higher investment costs then what is required for the use of methanol or conventional fuels.

The use, bunkering and storage of methanol is well-established and would require relatively low investment costs. Furthermore, the production of bio-methanol (bio-MeOH) has a relatively low LCOE, while the production of e-methanol (e-MeOH) is high and comparable to the cost of production of e-ammonia.

Storage, bunkering and use of e-LMG is well established, and the production cost is relatively low compared to the other alternatives with a LCOE close to that of e-hydrogen and ammonia from steam reforming coupled with CCS.

3.1.7 Safety aspects

The regulatory and safety maturity levels of alternative fuels and vessel designs must be assessed alongside their cost, environmental impacts, readiness, and availability. The type of safety concerns differs between fuels, propulsion technologies, and ship types at ports, with, for example, human exposure risk being higher for passenger vessels such as ferries and RoPax (Brynolf et al., 2023).

With the speedy implementation of new fuels to meet the sustainability requirement, it is critical to ensure that regulatory safety requirements are developed and introduced as individual assessment is time consuming and creates uncertainty (UNCTAD, 2023). DNV (2022) identified regulations and safety aspects as two of the primary barriers to wider adoption of hydrogen in the maritime sector, alongside cost. Inadequately detailed class requirements make it difficult to determine what fulfills safety standards, leading to increased costs and work for individual actors. Safety procedures and requirements is currently often assessed per vessel. For example, the International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels (IGF Code) dictates that the use of all low-flashpoint fuels and gases must include a risk assessment. For methane applications this only needs to be applied when specifically identified in the prescriptive requirements, but all other fuels require a full risk assessment for each use case.

Regulatory framework for safe installation, bunkering and use of the fuel is currently lacking for some alternative fuels (Jivén et al., 2020). In 2022, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping MMMCZCS (2022) made an analysis of the current gaps in legislation for alternative fuels. The analysis states that though class rules/guidelines are available for the fuels discussed in this report (bio-oils, methane, methanol, LPG, ammonia, and hydrogen), several other maritime rules and standards must be further developed. This includes IMO safety of Life at Sea (SOLAS) for all fuels and bunkering standards for most (not methane nor bio-oils). Hydrogen and ammonia have the least extensive list of frameworks developed.

There are safety regulations in place which also applies to handling of alternative fuel, such as for example SOLAS at IMO level and SEVESO for use within the EU. Regional requirements might also apply. For example, introduction of methane, hydrogen, or ammonia in a Swedish port may necessitate renewal, procurement, or updating of permits for flammable substances according to the Law on Flammable and Explosive Substances (LBE). Standards and regulations to mitigate risks for new marine fuels are under development (See Table 16). For example, the inclusion of alternative fuels in the often-used fuel quality standard ISO 8217:2017 is under development and a new version, currently noted as ISO/AWI 8217, will likely be published in 2024 (ISO/TC 28/SC 4, 2024b).

Table 16 summaries some key risks for the fuel alternatives assessed in this report.

Table 16. Summary of main safety aspects for alternative fuels.

Fuel	Regulatory status	Port and bunkering	Toxicity	Flammability	Onboard aspects	Additional key risk factors
Methanol	Currently used in commercial operations. Fuel quality standards for methanol is under development (ISO/TC 28/SC 4, 2024a)	No expected obstacles regarding fuel safety and operations (MMMCZCS, 2022).	Considered toxic but is biodegradable, which limits its distribution range in case of a leakage.	Despite having a low flashpoint (11-12°C), methanol's safety management is an established practice	There are no expected obstacles regarding fuel safety and operations (MMMCZCS, 2022).	
Methane	Currently used in commercial operations. A fuel quality standard is in effect (ISO 23306:2020) and bunkering regulations are available.	No substantial hindrances to the safety and efficiency of operations for the use of methane as a maritime fuel (MMMCZCS, 2022). However, the risks differ from those of conventional fuels and knowledge among the port personnel of correct safety management is therefore key.	Methane is non-toxic	Leakages might lead to formation of explosive mixtures (explosive limit in air 5% - 15%).	Risks differ from those of conventional fuels and knowledge among the crew of correct safety management is therefore key.	Liquefied methane is a condensed gas (which can generate high pressure with temperature increase), and risk of suffocation through asphyxiation (Bach et al., 2022).
Hydrogen	Major challenges for safety and fuel management (MMMCZCS, 2022). Regulation, under development.	Potentially high risks for port personnel to be addressed for large scale bunkering. Good practices and safety infrastructure must be in place before hydrogen is managed at scale in ports.	Hydrogen is non-toxic.	Large flammability range in air (4-75%) (Stenersen & Lundström, 2023) and prone to leakage. Very small leakage in unventilated areas can accumulate to combustible concentrations (Bach et al., 2022).	Potentially high risks for crew, and safety regulation and standards are under development.	Same risks as for methane, and in addition: high degree of ventilation and keeping potential ignition sources separate from potential leakage are key safety concerns. Gaseous hydrogen emits little to no detectable signs upon release. Difficult to detect a fire as it burns with a nearly invisible flame.
Ammonia	Major challenges for safety and fuel management which has not yet been solved. New safety regulations are necessary (MMMCZCS, 2022).	Despite already managed as a commodity chemical (LPG carriers currently manage safety issues for ammonia as a cargo), its use as a fuel poses heightened safety risks for port personnel. Good practices and safety infrastructure must be in place before it is managed at scale in ports.	Highly toxic for humans and other animals. Small doses pose lethal risks Significantly higher toxicity than diesel and methanol (Klerke et al., 2008).	Leakages of might lead to formation of explosive mixtures (explosive limit in air 15% - 28%) (Hansson et al., 2020).	Corrosive, which must be considered when vessel and distributions systems are designed (Hansson et al., 2020).	Additional risks are associated with liquefied ammonia being a condensed gas (which is cold and can generate high pressure with temperature increase),
Liquid marine biofuels (diesel types)	Variety in production processes and feedstocks calls for updated fuel quality standards to ensure adequate biofuel specification and maximum/minimum property ranges (European Maritime Safety Agency, 2022)	For liquid marine biofuels, such as HVO, FT diesel, and FAME, there are no unresolvable or unmitigable risks for marine applications (European Maritime Safety Agency, 2022)	Depends on the production processes and feedstock used in fuel production. (European Maritime Safety Agency, 2022).	Depends on fuel type, but like conventional fuels	Might require more frequent surveys and cleaning as well as additional crew training (European Maritime Safety Agency, 2022).	-

3.2. National, EU and IMO Polices and EU funding programs

On the global level, IMO, the United Nations agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships has within its Marine Environment Committee (MEPC), in July 2023 adopted a Strategy on the Reduction of GHG Emissions from Ships (MEPC, 2023a). The strategy sets a common vision and a goal of achieving net-zero GHG emissions by or around, 2050. Also, guidelines on life cycle GHG intensity of marine fuels (LCA guidelines) containing a well-to-wake perspective has recently been adopted (MEPC, 2023b).

The IMO strategy towards net-zero GHGs from shipping is planned to consist of two main elements, a technical part, with a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity; and an economic part, based on a maritime GHG emissions pricing mechanism. Several policy proposals have been proposed within the IMO. The communicated plan is that the specific measures/policies and their constructions will be discussed and decided on during 2024 – 2026.

In the EU there are several policy initiatives linked to the introduction of alternative marine fuels including the following.

Inclusion of shipping in the EU emission trading system (ETS): According to the amendments to the EU emission trading directive (adopted in May 2023) shipping is included in the EU ETS from beginning of 2024 (European Parliament and Council, 2023a). Intra-EU traffic (including port emissions) and 50% of the emissions from incoming and outgoing traffic covering ships above 5 000 gross tonnages are included. CO_2 emissions are covered initially but methane (CH_4) and nitrous oxide (N_2O) will be included from 2026. In 2024 40% of the emissions will be covered, increasing to 70% in 2025 and then full inclusion from 2026. With full inclusion the CO_2 emissions from shipping will represent about 8% of all the emissions covered by the EU ETS (Flodén et al., forthcoming). This policy is expected to provide important incentives to reduce shipping GHG emissions (Flodén et al., forthcoming). However, to promote a large-scale shift to renewable fuels a relatively high allowance price is needed (Flodén et al., forthcoming).

The FuelEU Maritime Regulation: The Fuel EU Maritime aims to promote the use of renewable and low-carbon fuels in EU related shipping (European Parliament and Council, 2023b). This by reducing the GHG intensity of the energy used on-board of ships by 2% in 2025, 6% in 2030, 14,5% in 2035, 31% in 2040, 62% in 2045 and 80% in 2050, see Figure 22. It also contains requirements for container ships and passenger ships, to use onshore power when in at berth from 2030 or 2035 depending on the port and ship type.

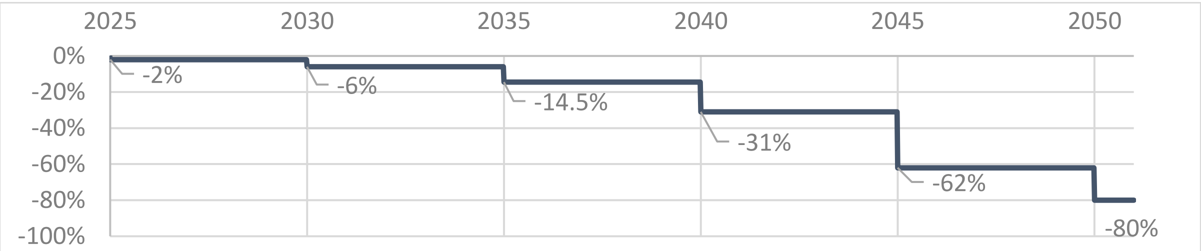


Figure 22. Development of the greenhouse gas intensity of the fuel in relation to 2020 in accordance with FuelEU Maritime.

The Directive on Deployment of Alternative Fuels Infrastructure: The revised Directive on Deployment of Alternative Fuels Infrastructure (final act signed September 2023) include mandatory targets for the supply of shore-side electricity at ports (mainly for container ships and passenger ships by 2029 while for inland waterways ports partly from 2024) (European Parliament and Council, 2023c). Provision of refuelling points for liquefied methane in ports are also called for.

The Renewable Energy Directive: According to the updated Renewable Energy Directive (RED, which entered into force in November 2023) at least 40% of the total energy mix must come from renewable energy sources (recently revised from previous level of 32%) (European Parliament and Council, 2023d). RED has a special focus on sectors which have had a slow development, such as the transport sector.

The Energy Taxation Directive: In the proposed revision of the EU's Energy Tax Directive that aims to make the taxation of energy products more equal and in line with the climate objectives of the EU, the suggestion is to tax also shipping (European Council, 2023). This means that marine fuels and electricity for transport within the EU must be taxed. However, alternative fuels such as biofuels and electrofuels will receive different tax levels. Separate lower minimum tax levels are proposed for fuel used for ferries and fishing and cargo vessels within the EU to avoid the risk of them bunkering outside the EU. The minimum tax levels are also proposed to be stated per energy unit instead of per volume. No final agreement has yet been reached on the revision of the Energy Taxation Directive, and it is uncertain whether this will be decided or not in a near future.

The European Hydrogen Bank: The European Hydrogen Bank provides financial support for green hydrogen production (European Commission, 2023). The aim is to bridge the costs incurred for hydrogen produced with renewable energy instead of fossil fuels and the maximum support level is currently 4.5 EUR per kg. Subsidies are given to the producers who request the least support in the form of a fixed price per kg of hydrogen produced during a maximum of 10 years of operation. Furthermore, producers should support their bid with a memorandum of understanding from off-takers covering part of the production.

In Sweden domestic shipping is included in the target for 2030 to reduce the emission from domestic transport by 70% to 2030 compared to 2010 (Swedish Government, 2016). For 2045 the target for Sweden is to have no net GHG emissions. The transport sector is however expected to have to reach zero emissions by 2045. Swedish related international shipping is not covered by the targets.

On national Swedish level, the government investment subsidy **Klimatklivet** is making it possible to invest in fossil-free and green technology. The support is mainly given to the measures that provide a high and lasting climate benefit by reducing emissions of GHGs. Klimatklivet was introduced in 2015 and over 5 200 applications have been granted until March 2023, which is expected to reduce GHGs by 2.6 million tonnes per year while the measures are active (Naturvårdsverket, 2023). For shipping, several applications regarding electricity and charging infrastructure have been granted, for example in Port of Gävle, Stockholm ports and Port of Gothenburg. Investment support has also been granted for several new electric-powered ships and for the conversion of conventional powertrains to fossil-free technology.

Another Swedish support system is called **Industriklivet** (Energimyndigheten, 2023). Within this long-term initiative, grants can be awarded for feasibility studies, research, pilot, and demonstration projects. Industriklivet comprises a total of approximately 1,354 million SEK in 2023 and can finance projects running until 2030 within the following areas:

- GHG emissions from the process industry
- Negative emissions, for example carbon capture and storage
- Strategically important initiatives in industry

There are a few other policies aimed at reducing the GHG emissions from shipping in Sweden, which include (i) **environmentally differentiated fairway fees** that consider a number of different environmental aspects, of which climate adaptation is an important part, (ii) **Ecobonus** which is an environmental compensation for the transfer of goods to shipping that is aimed at shipowners and is intended to stimulate new maritime transport systems, and (iii) some ports, often municipally owned, have introduced **environmentally differentiated port charges**, giving environmental discounts to shipping companies that for example chooses to invest in electrical connection on board a ship or in other more environmentally friendly ships.

Furthermore, **the Industry´s Energy and Climate Transition programme** can give financial support to research, development and demonstration projects contributing to more efficient energy use, zero net GHG emissions by 2045 and improved efficiency for resource use (Energimyndigheten, 2023). The programme runs until 2026 and comprises a total of 186 million SEK.

Similar subsidies, support systems and initiatives have been introduced in other European countries.

3.3. National, regional, local perspective

From a local perspective, ports, shipping companies, and local energy producers and suppliers that wish to use the port's energy infrastructure, can work together to find suitable bunkering and charging strategies for a specific region.

An example of how local actors can come together is found on the Island of Gotland, on the east coast of Sweden. The shipping company Gotlandsbolaget (operating high-speed ferries for passengers and cargo between Gotland and the mainland of Sweden) and local energy producers on Gotland have started collaborations where the goal is for existing ships to be able to bunker locally produced biogas from the Island of Gotland. Gotlandsbolaget invests and becomes a partner in the Gotland company EnergiSkiftet Sverige AB, the parent company of Biogas Gotland, BroGas and Gotlands Fastbränsle (Gotlandsbolaget, 2023). This investment lays the foundation for continued growth of the biogas investment on Gotland and enables increased access to biogas in Gotland traffic. A presumed prerequisite is that the biogas that is produced locally, but still some distance from the port, is refined to the quality and form that enables transport and storage at the port as well as to enable bunkering, which requires new infrastructure.

This kind of new collaboration have been observed with new actors and is an important driver for the local actors to promote the region by offering alternative fuels for industries and the transport sector, including shipping. What we have also seen is that local actors are depended on larger actors due to the complexity of the task to facilitate and set up production facilities, and the large costs and risks involved. In Sweden, many ports and local energy companies are owned by the local governing body. There are many reasons why ports in general, and these municipally owned companies, in particular, may be reluctant to invest in new energy project. First, there are large risks and costs involved, and an uncertainty of how supply and demand for a specific low-carbon fuel will develop over time. Second, there may be a lack of knowledge and experiences necessary to handle these large complex projects on a local level. In Sweden, there are some examples where municipally owned companies have previously invested in the energy sector, which have entailed large costs but little benefit. This may have led to increased caution.

The local perspective is further investigated in the Blue Supply Chains' report "Roadmap to provide green energy for transport chains starting/ending in ports – the case of Umeå.

3.4. Development over time

As highlighted earlier in Chapter 3, the introduction of regulation aimed at lowering the climate change impact of the shipping sector is expected to lead to a change in fuel used in the sector. The first shift in fuel motivated by environmental concerns has already occurred and was primarily driven by regulation of sulfur emissions. As shown in *Chapter 3.1.4 Environmental aspects,* different fuels do not only differ in terms of their climate change impact, but also in how they affect other environmental issues such as the emissions of SO_x effect on acidification and human health. The global and regional caps on sulfur content in the fuel used onboard vessels led fuels with lower sulfur content being used, and motivated moves to fuels such as LNG. Figure 23 shows how the yearly emissions from international and domestic shipping in Sweden relate to the introduction of new regulations.

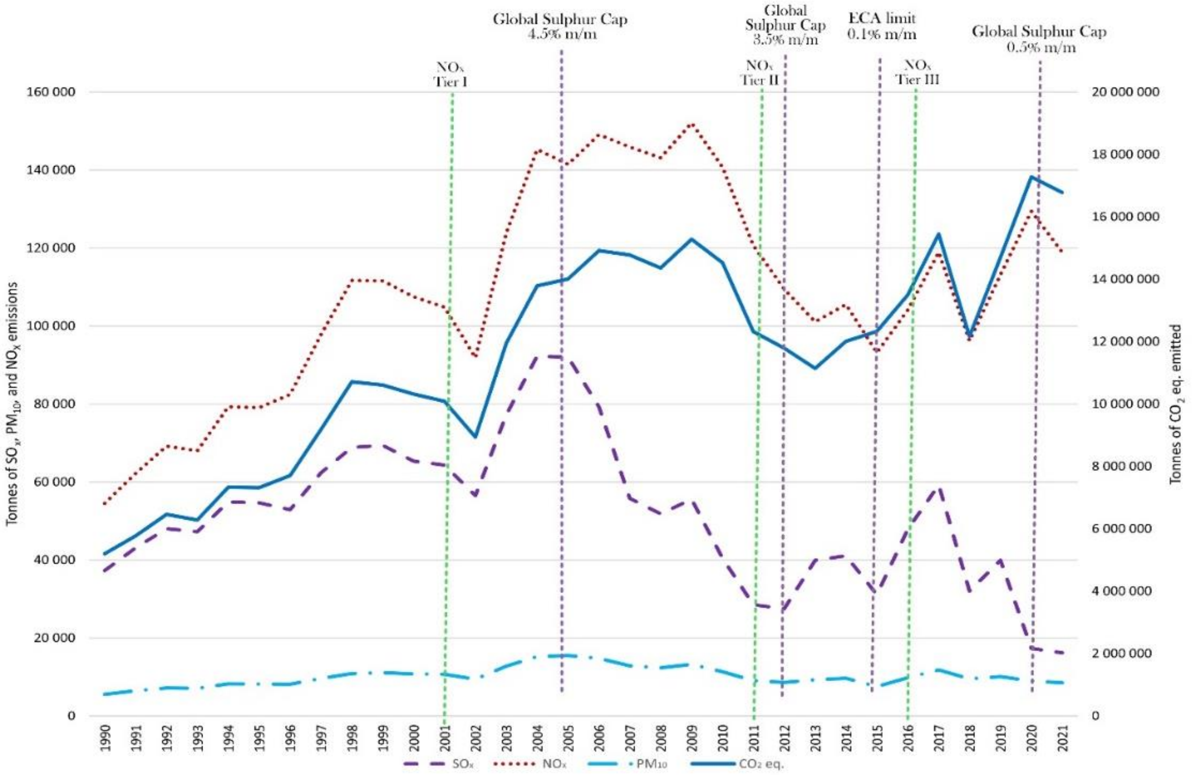


Figure 23.The yearly emissions of Greenhouse gases (in CO_2 equivalents), Sulphur (in SOx), Nitrogen oxide (in NOx), and Particulate matter (in PM10), from 1990 until 2021 in Swedish domestic shipping and Swedish international shipping (SCB, 2022). Figure from (Malmgren et al., 2023) as is used with the permission of the author.

Globally, the maritime sector is anticipated to experience continued economic growth, driven by increasing global trade and economic activity. UNCTAD (2023) expects maritime trade to grow by 2.4% in 2023 and more than 2% between 2024 and 2028. Emerging markets in Asia, particularly China and India, are expected to be key drivers of this growth, along with continued expansion in established markets such as Europe and North America. Growth in freight volumes, destinations served, and overall market size are projected across all regions, albeit with regional variations influenced by economic trends, trade agreements, and infrastructure development. This expansion will lead to increased pressure on the environment, and IMO:s short-term climate change goal (i.e. 2030) is targeted at reducing CO_2 emissions per transport work rather than the sectors total GHG emissions (MEPC, 2023a). However, the long-term goal of the IMO is to reach net-zero GHG emissions by or around, i.e. close to, 2050. The latest strategy (adapted 2023, to be updated in 2026) includes a goal for the uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources. By 2030, they should represent at least 5%, aiming for 10%, of the energy used by international shipping.

In Europe, the market for sustainable maritime fuels is expected to grow significantly, driven by ambitious environmental regulations such as the targets set for lower GHG intensity for fuel over time in FuelEU maritime (Figure 22), and public pressure for more sustainable transportation. The use of zero or near-zero GHG emission technologies and energy carriers has increased in Sweden over the past decades (Holmgren and Polukarove, 2021). Some examples are the RoPax vessel Germanica thar was retrofitted to a dual fuel system with diesel and methanol propulsion in 2015, the ferries Aurora and Tycho Brahe that have used battery-electric propulsion since 2018, and methane propelled vessels that are both in use (more than half of the alternative fuel bunkered in Sweden on an energy basis in 2021 was LNG (Swedish Energy Agency, 2023b)) and in the order books (DNV, 2023a). Several research and industrial collaboration projects are also ongoing in Sweden, e.g. *Hydrogen fuel cells solutions in Nordic shipping* (HOPE) (Hansson et al., 2023), and *Hydrogen, Ammonia and Methanol in hydrogen hubs in the Nordic region* (H2AMN), as well as initiatives in form of innovation centres such as *Centre for Hydrogen Energy Systems Sweden* (CH2ESS) at Luleå University of Technology.

According to DNV (2023a), around half of the vessels in the order books in 2023 will be able to operate on alternative fuels like LNG and methanol. However, widespread adoption of alternative fuels is still in its early stages and will likely take several decades to fully materialize. DNV (2023a) estimates the maritime sectors demand for carbon neutral fuel to be 280 million tonnes by 2030, which is around 3% of the expected global demand. Forecasts and assessments differ in which fuel will be the primary fuel used in the sector in the future. Some report ammonia as the likely future fuel, while others highlight methanol or LBG (MMMCZCS, 2022; DNV, 2023a). Battery-electric is expected to have a limited application also in the distance future due to range restrictions but will probably be common as an additional energy source along with a fuel. Maersk Mc-Kinney Møller Center for Zero Carbon Shipping predicts an increased use of both methanol and ammonia onboard vessels based on vessels currently on order (MMMCZCS, 2022).

The transition of the maritime sector to sustainability is a complex and multifaceted process, requiring collaboration between governments, industrial stakeholders, and civil society (see chapters *1.2 Stakeholder landscape*, *1.3 Driving forces for changes and market aspects,* and *5.1 Stakeholders' view on present and future development*). While significant challenges remain, including technological barriers (*Chapter 3.1.1 Technical description and maturity level*) and regulatory uncertainties (*Chapter 3.2 National, EU and IMO Polices and EU funding programs*), there is growing momentum towards a more sustainable future for the maritime industry, with alternative fuels playing a crucial role in achieving this goal. It is difficult to project the future fuel production and use of zero or near-zero GHG emission technologies as discussed in *Chapter 3.1.2 National Production capacity*. As shown in *Chapter 3.1.4 Environmental aspects*, a shift from to fuels with lower GHG emissions could reduce the emissions from the sector with over 90% depending on the sectors energy use and the fuel production pathways. However, the competition with other sectors will be significant. Alongside regulation and legislation, introduction of new business models, such as aimed public procurement or direct cargo owner initiatives, are expected to accelerate the transformation of the sector. The cost of zero or near-zero GHG emission technologies and energy carriers are higher than conventional technologies, as shown in *Chapter 3.1.6 Economic aspects,* and will require additional drivers (Malmgren et al., 2023).

4. Emission free inland waterways connecting seaport and hinterland – Lithuanian case

4.1. Background

This project initiative is closely interlinked with the EU's environmental goals - specifically, a 90% reduction in transport greenhouse gas emissions by 2050, with an interim target of 55% by 2030. The focus is on transforming IWT, a significant sector in the European transportation landscape, from its reliance on traditional fuels to alternative, more sustainable energy sources, primarily electricity.

The extensive network of European inland waterways, stretching over 40,600 km, is the backbone of this transformation. A primary challenge in this journey is the development and deployment of a comprehensive charging infrastructure for electric inland waterway transport (IWT). This aspect is crucial but faces a significant bottleneck: the deployment of electric vessels is interfering by the shortage of charging facilities, and simultaneously, the construction of such infrastructure is contingent upon the anticipated use of electric vessels.

To address this challenge, Lithuanian Inland Waterway Authority plays key role in which have to:

- look at the way in which the EU adopts standards and coordinates and supports Member States deployment of electrical charging infrastructure.
- obtain information from several sources (Commission, national authorities, and other stakeholders) to gain first-hand experience as users of charging infrastructure.
- obtain information of harmonized payment systems with minimum requirements and adequate user information on real-time availability and billing details of charging stations.

The project explores the potential of alternative fuels, with electricity at the forefront. However, this path is not without obstacles, notably the high initial cost and limited energy density of batteries, which restrict the range of electric vessels. In response, Lithuanian Inland Waterway Authority participates in vessel design, particularly for shallow water navigation, and will engage in a pilot project to evaluate and validate electric technology under real sailing conditions. This includes a detailed analysis of energy consumption in different water levels and vessel speeds, essential for determining the strategic placement of charging stations.

In parallel, Klaipeda Science and Technology Park is making significant strides by developing a modular propulsion system, potentially revolutionizing the concept of emission-free inland water vessels. This system is designed to be universal, adaptable to any vessel within the EU and potentially beyond, and capable of utilizing various power sources, including batteries or alternative fuels like hydrogen or ammonia. A crucial aspect of Klaipeda Science and Technology Park's approach involves a collaborative strategy between shipyards and ship owners, focusing on the practical application and testing of modular, containerized solutions.

The reason of these efforts is the creation of the first European zero-emission e-waterway. This landmark project, a collaborative effort of Lithuanian Inland Waterway Authority and Klaipeda Science and Technology Park, aims to transform an existing waterway into a model of sustainability and innovation. This pilot project is not just a testbed for modern technologies but also a source of valuable insights for the entire EU and Baltic Sea Region. It addresses key operational questions, such as the optimal distribution of charging points, the specifications of charging stations, and real-world data on energy consumption in various navigational conditions.

The outcome of this comprehensive initiative is the foundation of an integrated strategic roadmap for electric IWT transport mobility in the EU. This roadmap is provided to guide stakeholders and policymakers towards the achievement of the EU's environmental objectives, particularly in developing a robust charging infrastructure, thereby marking a significant step towards realizing the goal of a carbon-neutral transport system. This journey, characterized by innovative solutions and collaborative efforts, is a testament to our commitment to a sustainable and cleaner future in maritime transport.

4.2. Nemunas river and ports characteristics

The Inland Waterways Project along with the Nemunas River represents a purpose of enhancing connectivity and economic vitality in Lithuania. Covering from Kaunas to Klaipeda, the project seeks to transform the Nemunas River into a thriving waterway, unlocking its potential as a key artery for commerce and transportation, see Figure 24.

Figure 24. Connection between Kaunas to Klaipėda.

In 1997 the Republic of Lithuania signed a European Agreement on Main Inland Waterways of International Importance (AGN agreement), according to which the aforementioned waterway is an inland waterway of international importance E41 (the length – 291.2 km).

The Nemunas River Navigation enhancement is underway to address critical navigational challenges that have persisted over the past two decades. Technological advancements, including the implementation of a River Information Service (RIS) system, promise to enhance safety and efficiency in navigation, further bolstering the infrastructure of the Nemunas River.

4.2.1 Klaipeda port

The presence of ice poses minimal hindrance to navigation, occurring for a brief period of up to two weeks annually in January/February. Klaipėda port (Figure 25) stands as the northernmost ice-free Baltic Sea port, offering a competitive advantage over other ports, particularly in winter. Equipped with the KIPIS freight movement information system and the LUVIS vessel traffic management information system, the port ensures efficient operations and meets the standards of the International Ship and Port Facility Security (ISPS) Code, enhancing its status as a strategic hub for maritime trade and security. Plans for onshore power supply connections and infrastructure upgrades signal a commitment to sustainable and efficient operations.

Figure 25. Port of Klaipėda.

4.2.2 Kaunas Marvele Port

The Kaunas Marvele cargo berth, strategically located near Via Baltica, can serve as a universal port accommodating passenger and recreational services. Its development unfolds in three progressive phases.

Phase I involves the construction of a 120-meter quay, sufficient for 110-meter ships, along with 0.65 hectares of concrete pavement (Figure 26).

Figure 26. Kaunas Marvelė port after Development phase I.

Phase II focuses on installing handling equipment to facilitate cargo loading and unloading, projecting a capacity of 68,344 TEU per year and storage capacity of 267,453 TEU, see Figure 27.

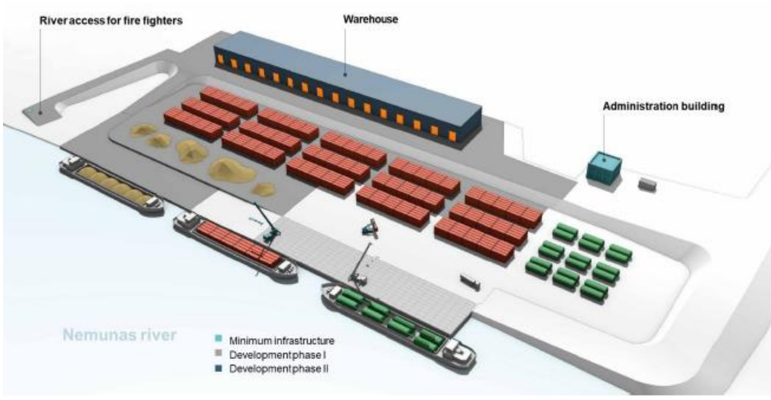


Figure 27. Kaunas Marvelė port after Development phase II.

Phase III envisions further expansion, designation a 10.7-hectare area for cargo port expansion, potentially extending the quay length to 480 meters and platform area to 8.5 hectares, announcing a new era of maritime commerce and infrastructure growth, see Figure 28.

Figure 28. Kaunas Marvelė port after Development phase III.

4.2.3 Jurbarkas port

Jurbarkas (Figure 29) lacks transshipment facilities for Inland Waterway Transportation (IWT), highlighting the necessary for construction. Specifically, facilities should accommodate the exchange of battery containers, with minimal operational requirements for cranes or reach stackers. Alternatively, crew members of docking ships could handle these operations on-site, ensuring streamlined functionality and operational efficiency.

Figure 29. Current situation at Jurbarkas.

Historically, Jurbarkas served as a significant shipping center during the Soviet Period, constructed in 1965. Equipped with overpasses facilitating gravel loading even during low river water levels, it emerged as a key loading point in Lithuania. Construction materials and wood were the primary commodities transported via the Nemunas River during that era. (Figure 30)

Figure 30. Jurbarkas cargo port in 1966.

4.3. Technical study on vessel design for zero-emission inland navigation corridor

Regarding to the primary conclusion of first vessel design, we have also considered alternative power drives. Table 17 contains an overview of the criteria that played a role in the assessment.

Table 17. Comparison of different powertrains.

	Diesel electric (diesel unit)	**Methanol electric** (methanol unit)	**Hydrogen Fuel Cell**	**Battery electric**
Policy relevance	Additional measures needed to achieve zero emission	Additional measures needed to achieve zero emission	Zero emission ready option	Zero emission ready option
Techno-logical readiness	Proven technology, diesel widely available	Not widely applied in IWT. Lower energy density of methanol requires larger tank	Not widely applied in IWT. Lower energy density of hydrogen requires larger tank. Hydrogen not widely available and costly.	Application field typically shorter distances with no strong current. High weight of batteries.
Finance	Question how to finance delayed modification to hydrogen fuel cell	Question how to finance delayed modification to hydrogen fuel cell	Larger financing gap due to higher CapEx although eligible for EU funding & financing	Larger financing gap due to higher CapEx although eligible for EU funding & financing
Legal		Methane is hazardous/toxic substance, this involves ADR[5] issues. Not yet CESNI[6] approved.	Hydrogen storage facilities need to be realised. This involves ADR issues	Charging infrastructure and grid connection to be realised, at multiple locations along the route

Based on this, it was concluded that battery electric ships are the most beneficial compared to other options.

The pre-feasibility study, developed by the Western Shipyard Group and commissioned by LIWA/VVKD, focused on designing a pushboat and barge system for cargo transportation between the port of Klaipeda and Kaunas Marvele port via the Nemunas River. The design aimed to navigate shallow waters effectively.

The pusher’s design was based on electric propulsion, utilizing batteries as the power source, with the assumption that two battery containers would suffice for a complete journey. These batteries, housed in shipping containers, were to be changed only at Klaipeda and Kaunas.

Technical parameters of the pusher included:

- Breadth width of 8-10 meters,
- Length of 20-26 meters,
- Ship weight of 70-90 tons, a two-screw hull with dual engines of approximately 320 kW each,
- Maximum draft of 1.2-1.5 meters.
- The design also considered speed variations based on load and direction – downstream without load about 15 km/h, upstream about 10-12 km/h.
- Need for hydraulic height adjustment for navigating under the Queen Louise Bridge.

The dimensions of the pusher and barge were specified as 27.8x9.2x1.24 meters and 74.4x15.85x2.05 meters, respectively. The design initially assumed battery containers of 1.5 MWh, but it was noted that ZES containers could provide a higher capacity of 2.7 MWh.

Concordia Damen was commissioned to review this design. Their analysis highlighted a significant issue: the pusher-barge combination might not complete the upstream journey on two battery loads due to the higher energy requirement for upstream travel which takes an estimated 2-3 times more energy than downstream. Also, sailing conditions are not easy: the distance between Klaipeda and Kaunas is about 260 km and currents can reach 1 m/s. This was escalated by the increase in resistance at higher sailing speeds, leading to a disproportionate rise in required power and energy consumption. Figure 31 below illustrates this link between speed and required power.

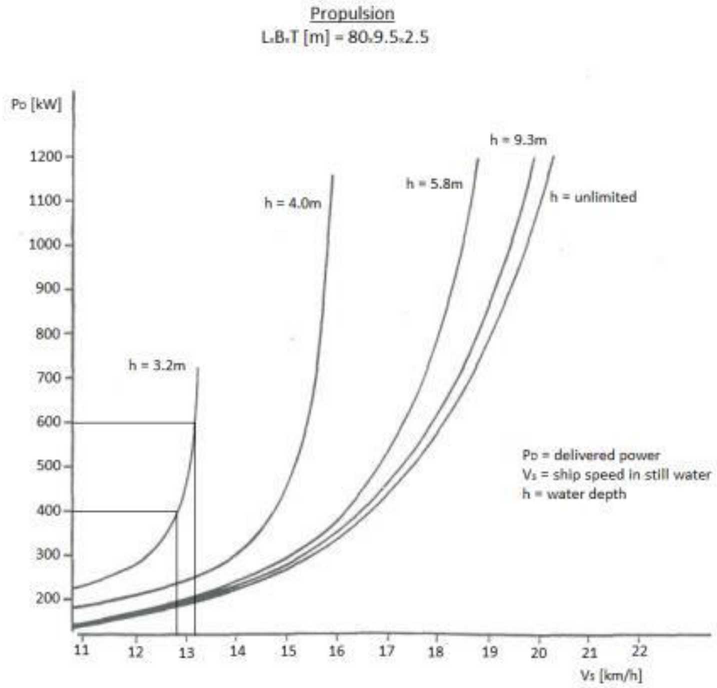


Figure 31. Power-speed curves example for a given vessel.

An analysis of the sailing route from Rotterdam to Duisburg, comparable to the Nemunas route, indicated that the energy requirements at different sailing speeds were significantly higher than anticipated.

- At a vessel speed of 8 km/h upstream, 17 MWh is required, corresponding to 7 ZES battery containers in case of battery electric propulsion.
- A vessel speed of 10 km/h upstream requires 20 MWh, corresponding to 8 ZES battery containers in case of battery electric propulsion.

The primary conclusion from this review was that the initial design was not feasible for electrical sailing on the Nemunas River. Even with higher capacity ZES battery containers, the number of containers required for a single upstream voyage was impractically high (8 to 12), mainly due to the high resistance of the convoy. The design of the flat barge, akin to a pontoon, was deemed suboptimal for energy efficiency.

We have done the optimization phase of the preliminary design focused on enhancing energy efficiency and adaptability of the barge to different cargo types, such as containers and bulk. A significant aspect of this optimization was the assumption that by reducing the sailing speed to 8 km/h in the upstream direction, there would be a 25% energy saving. This reduction in energy consumption is attributed to the proposed use of narrower barges, which would decrease the sailing resistance of the convoy.

The specific energy requirements for the journey from Klaipeda to Kaunas, at the optimized speed of 8 km/h upstream, were calculated to be 13 MWh. This translates to a need for five ZES battery containers. However, the design aimed to further reduce this requirement. By introducing a stopover and battery change at Jurbarkas, the number of battery containers needed on the pusher could be lowered to three, making the concept more viable.

This approach not only reflects a significant improvement in the energy efficiency of the vessel but also demonstrates a practical solution to the challenge of battery capacity and vessel autonomy. The optimization phase, therefore, marks a crucial step towards the financial feasibility of the project, with considerations for operational practicality and energy consumption at its core. The adaptation of the barge design to reduce resistance and the strategic use of battery changeovers are key factors in achieving a more efficient and feasible vessel design for this specific route.

4.4. Key Stakeholders

The feasibility of implementing a new service is evaluated by analyzing both demand and supply factors. Consequently, it is essential to engage local market stakeholders to ascertain their willingness to utilize or invest in the new service. Key public authorities, whose contributions may include legislative support or financial backing, have been identified. Figure 32 below delineates shows the primary stakeholders and their respective interests in the project.

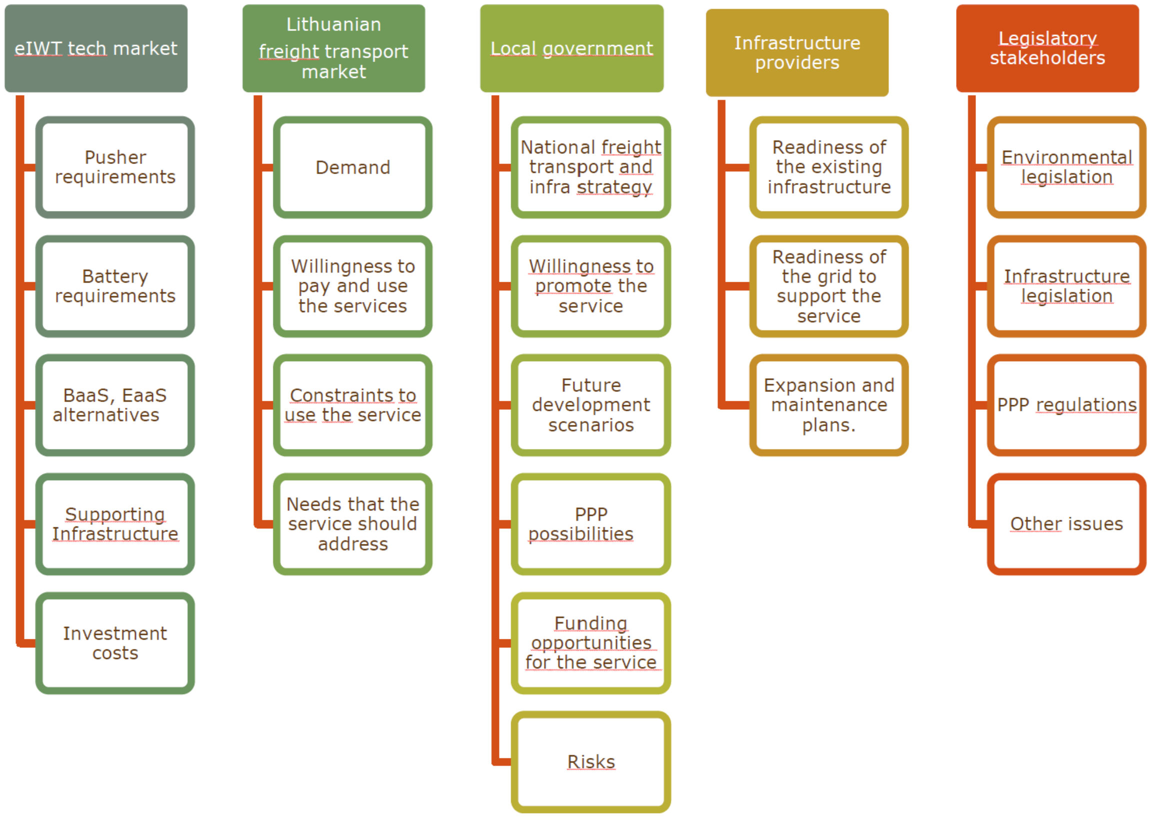


Figure 32. Key public authorities and their respective interests in the fossil free inland waterway project.

To assess the feasibility, legal, and institutional framework of the proposed service, key stakeholders were engaged to identify potential demand, service frequency, and technical requirements. The identified stakeholder categories and their contributions were as follows:

- **eIWT Vessel Technology Market**:
  - Pusher and Barge Requirements
  - Battery and Charging Equipment Requirements
  - Providers of Battery-as-a-Service (BaaS)
  - Supporting Infrastructure Needs
  - Investment Costs
- **Lithuanian Freight Transport Users (Logistics Service Providers and Shippers)**:
  - Level of Demand for the New Service
  - Willingness to Use and Pay for the New Services
  - Constraints and Requirements to Use the Service
  - Interest in Participating in the Service Launch
  - Specific Requirements for the New Service
- **Infrastructure Providers (Klaipėda, Marvelė Ports, and Electricity Providers)**:
  - Readiness of the Existing Infrastructure
  - Grid Readiness to Support the Service
  - Expansion and Maintenance Plans

- **National Government**:
  - National Freight Transport and Infrastructure Strategy
  - Willingness to Promote, Subsidize, or Fund/Finance the Service
  - Future Development Scenarios
  - Public-Private Partnership (PPP) Possibilities
- **Regulatory Stakeholders**:
  - PPP Structures and Regulations
  - Infrastructure Legislation
  - Competition Legislation

Interviews were conducted with the following key stakeholders:

1. Port of Klaipėda
2. Association of Lithuanian Stevedoring Companies
3. EMMA Project Coordinator in Lithuania
4. Statistics Lithuania
5. Ministry of Transport and Communications
6. Central Project Management Agency
7. Competition Council of the Republic of Lithuania

Additionally, interviews were conducted with shippers and logistics service providers, encompassing 16 companies (detailed in Annex 4). A study visit to the Netherlands was organized to learn from Dutch experiences in shipbuilding, waterborne freight transport, the operation of zero-emission ships powered by battery containers (such as the Alphenaar, described in Annex 1), and the operation of the Battery-as-a-Service (BaaS) model.

4.5. Identification of necessary infrastructure measures

The project has appropriately identified and estimated the key components necessary for the establishment of the electric vessel service. The investment in electric pushers, barges, and battery containers is a significant step towards modernizing and greening marine transportation.

The detailed approach to port infrastructure, with specific attention to Jurbarkas, indicates a thorough understanding of the logistical and operational needs of the service. The proactive measures for cargo handling and battery management through the allocation of cranes and charging points demonstrate foresight in ensuring operational efficiency.

However, the investment in infrastructure, particularly the grid expansion at Jurbarkas, suggests a considerable upfront cost. It's essential to balance these costs with long-term operational savings and environmental benefits. Also, the assumptions regarding the shared responsibility of grid expansion costs with the grid operator should be confirmed to avoid any financial discrepancies.

Summary of Required Investments and Facilities:

1. **Port Infrastructure Investment:**
   - Existing Facilities: Klaipeda and Kaunas Marvele ports have quays and mooring facilities suitable for 110 m ships.
   - Upgrades Required: Jurbarkas requires significant development, including quays, mooring facilities, cargo storage areas, and charging stations.
2. **Charging Points and Cranes:**

- Charging Points: Three needed, one each at Klaipeda, Jurbarkas, and Kaunas
- Cranes: Additional cranes are necessary for managing freight and switching battery containers.

3. **Electricity Grid Connection:**
   - Connection for Klaipeda and Kaunas Marvele port.
   - Grid Expansion at Jurbarkas:

Overall, this addresses the technical, operational, and infrastructural aspects required for the successful implementation of the electric vessel service. The focus on sustainable solutions, such as electric propulsion and the setup of efficient charging infrastructure, aligns well with contemporary environmental standards and EU directives on green transportation.

4.6. Required energy and infrastructure resources to provide recharging power between Klaipeda and Kaunas

The energy and infrastructure requirements have been well-defined, with clear specifications for the charging points, electric pusher vessels, battery electric containers, and the electric crane. The charging infrastructure at Klaipeda & Kaunas, capable of handling two battery containers simultaneously, is a key component, ensuring efficient turnaround times for recharging. The power requirements for the electric pusher vessels and the battery electric containers align with the operational needs of the service.

The electric crane is a critical piece of infrastructure for handling and swapping battery containers, and its specifications indicate a robust design suitable for the demands of the service. The electrical grid connection at Klaipeda is specified to meet the charging station's requirements.

Here is a detailed review of the energy and infrastructure resources required to provide recharging power between Klaipeda and Kaunas for the electric IWT (Inland Water Transport).

Energy Requirements:

1. **Charging Point at Klaipeda, Jurbarkas & Kaunas**:
   - The charging station has a capacity of 2 megawatts.
   - It can charge two battery electric containers simultaneously at a rate of 1,000 kW each.
   - Each container has a maximum capacity of 2516 kWh, and they can be fully charged in approximately 2.5 hours.

2. **Electric Pusher Vessels**:
   - Each vessel has a two-screw and two engines system, with a total engine capability of 410 kW.
   - The vessels operate at cruising speeds of 8 km/h upstream and 16 km/h downstream.
   - The vessels can push a maximum weight of 1,800 tons for a barge.

3. **Battery Electric Containers**:
   - 12 battery electric containers are to be constructed (Figure 33)
   - Each container has a total energy capacity of 2516 kWh
   - The containers are equipped with a Battery Management System (BMS) for safe operation and optimized battery life.

Infrastructure Resources:

1. **Electric Crane**:
   - Used for swapping battery electric containers.
   - Specifications include a total weight of 231 metric tons, a 355 kW engine, and specific electrical supply demands.

- The crane requires a supply voltage of 400 V / 50Hz and has internal voltages of 24 V DC and auxiliary 230V/400V AC.

2. **Electricity Grid Connection**:
   - A connection between the main electricity grid of the port of Klaipeda and the charging installation.
   - The voltage for the grid connection is 600V AC.

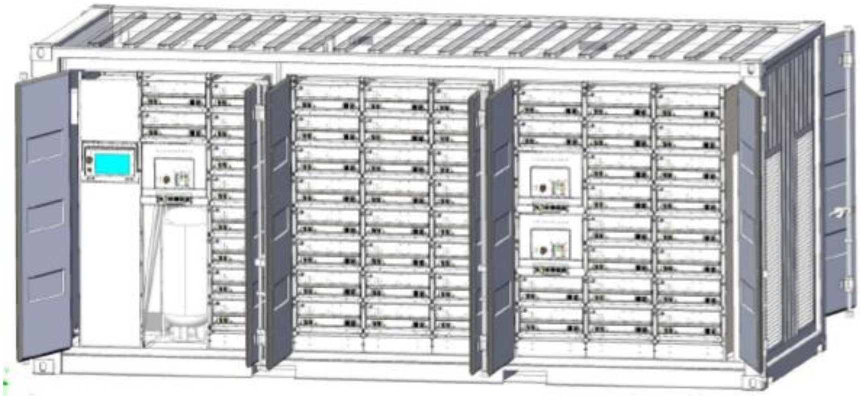


Figure 33. Battery container.

In summary, the project has thoroughly addressed the necessary energy and infrastructure resources to provide recharging power for the electric IWT service between Klaipeda and Kaunas. It reflects a comprehensive approach to establishing a sustainable and efficient electric inland water transport system. However, continuous assessment of the operational efficiency of these resources and their integration with the overall project logistics will be essential for the project's long-term success.

4.7. Next steps towards a “Zero Emission Waterway”

We are planning to engage in discussions with state grid providers to ascertain the timeframe required for the development and implementation of the necessary electricity power supply. Meetings are also scheduled with local city governments to secure permissions for the development and expansion of the Kaunas Marvelė and Jurbarkas ports.

Additionally, we plan to visit partners and attend conferences to gain insights from international best practices.

We intend to pilot the project of electric ships on the Nemunas River. Initially, simulations will be conducted to determine the precise technical specifications required for the vessels. We will collaborate with state energy companies to identify the necessary technical solutions for constructing the electrical infrastructure in the ports, enabling the charging of the vessels. Following this, a new public tender will be issued for the construction of an electric ship.

5. Green bunkering and charging strategy for ports - Swedish case

The overall aim of the Swedish case in Blue Supply Chains is to accelerate the transition to renewables and low-carbon fuels in the maritime sector. Thus, the aim of the green bunkering and charging strategy for Swedish ports are to create conditions for, and increase the possibility for, charging and bunkering of renewable low-carbon marine fuels in Swedish ports. The strategy provides a summary of the current situation and include a first assessment of the potential future demand for production capacity, bunkering and charging facilities in ports.

A guideline for the development of a national bunkering and charging strategy is included in *Chapter 6.2 Guidelines for the development of national/regional bunkering and charging strategy*. The purpose is to provide other countries around the Baltic Sea with a methodology to analyse supply and demand of fuels and charging facilities in ports to serve the shipping industry, but also surrounding industries and terminal equipment, today and in the future.

5.1. Stakeholders' view on present and future development

As described in *Chapter 2.2 Interviews*, energy companies, shipping companies, and ports have been interviewed. Data from the interviews, including the respondents view on present and future development, has been used within the analyses. A general description on the findings from the interviews is summarised in this chapter.

Energy companies

Energy companies, especially the ones interviewed, are looking into a wide variety of renewable fuels for shipping and other sectors. However, at present, it is mainly methanol production that the interviewed energy companies focus on for the shipping sector. Several companies are in the planning stages of establishing production of methanol and some examples of production volumes are presented in Table 3. The choice of fuel might change over time towards ammonia in case there is an increased demand from the shipping sector for this fuel. Many of the planned and proposed projects will be finalized in ten years' time or more but could, under the right circumstances, be established in a slightly shorter time.

In general, permit processes are highlighted as a difficulty, and finding customers with the right willingness-to-pay necessary for the projects to become commercially viable. Long-term contracts are lifted as an important success factor, and in many cases support schemes from the society for these types of projects. For many of the technologies that are of interest, high electricity prices have become a hindrance in several development projects. Moreover, long lead times for specific components can impede project progress.

Possible synergies with other operations, in the form of use of waste heat, use of carbon dioxide and if possible, also off-set of the bi-product oxygen from the hydrogen production process are sought after. However, this appears not to be in focus currently but rather in a later stage of the production development.

For hydrogen there is an expressed need for a hydrogen specific gas-grid, and it is seen by many stakeholders as complex from several different perspectives. Ammonia is disregarded by some stakeholders within shipping since it is associated with safety and security risks and is difficult from a working environment point of view as well as being associated with large risks for the local community.

Methanol has gathered a lot of interest from the energy companies, and stakeholders within the shipping sector are seen as especially interesting since they are expected to have a higher willingness-to-pay. Although methanol requires available power capacity and large volumes of captured carbon dioxide from fossil-free sources. Especially the access to bio-genic / fossil free carbon dioxide is seen as a potential future upcoming barrier for further expansion in order to fuel a large part of the shipping sector.

Bio-methane is also a viable option, with a few energy companies that already produce this renewable fuel. Since the gaseous fuel needs to be liquified to be used in shipping, it requires a liquefaction step in the production process, which is uncommon now. Although most large-scale biomethane producers are looking into adding a liquefaction step to reach new markets, such as shipping.

Shipping companies

The project has only interviewed a few shipping companies, but have knowledge on ongoing initiatives in Sweden through other research projects and assignments. From the stakeholders interviewed in this project, much of the focus is on LNG with the aim to use LBG more and more in the future, or as quickly as possible. Also, methanol vessels are in the shipping companies order books along with wind assistance. Land connection in ports and battery powered ships as a complementary energy source are becoming more common and opening opportunities for shipping companies.

The largest barrier for a shift towards renewable fuels are the increased costs. Presently, there exists an absence of demand and a reluctance to commit to payments within the maritime sector. However, there is optimism that this dynamic could shift with the potential implementation of the EU Emissions Trading System (EU ETS), which could incentivise stakeholders to prioritise cleaner alternatives. One such alternative gaining traction is the utilisation of Liquefied Natural Gas (LNG), with some ventures also incorporating Liquefied Biogas (LBG) into their operations.

Efforts to enhance the energy efficiency of ships are underway, reflecting a broader commitment to reducing emissions and operating costs. These initiatives include technological advancements, operational improvements, and the exploration of alternative fuels. However, challenges persist, particularly concerning the availability of suitable infrastructure and resources, leading to limitations on the widespread adoption of certain solutions.

Shift towards alternative fuels so far has mainly been that biogas (LBG) to a small extent has replaced LNG. It is clear in current discussions with stakeholders that divergent strategies can be observed within the maritime industry regarding renewable alternatives. While some sectors are embracing LNG and LBG as viable options, others are exploring different pathways, such as hydrogen or ammonia propulsion systems. This diversity underscores the complex landscape of sustainability initiatives within maritime operations. Several Swedish shipping companies has already started to use biofuels as a blend in occasionally and in some cases on a more regular level.

Despite the prevailing uncertainties, there are glimpses of optimism, with indications of potential orders for new vessels. This signals a growing recognition of the transition towards more environmentally friendly practices and technologies within the maritime sector.

Port authorities

The interviews with Swedish ports investigated the perspectives of ports regarding the adoption of renewable fuels, focusing on the prevalence of bunkering of renewable fuels, considerations for energy port designation, future plans for renewable energy integration, and the transition to renewable handling equipment. Findings reveal varying degrees of LNG bunkering activity, with ship-to-ship solutions predominating, except in cases where fixed infrastructure is available.

Ports exhibit diverse self-perceptions regarding their suitability as energy ports where several ports state that they are not suitable as energy ports. Factors such as location proximity to urban environments as well as space constraints in the port are cited as obstacles for the use of the port as energy port.

Regarding future plans for the ports, short-term and long-term strategies differ. Short-term future plans emphasize solar, wind, hydrogen, and methanol projects which are driven by customer demand. The long-term strategies are less defined when it comes to technology and are at the moment unclear but are similarly customer-oriented.

The majority of ports have transitioned handling equipment to renewable alternatives, with a prevalence of hydrotreated vegetable oil (HVO) and electric propulsion systems. Despite initial procurement costs, electricity emerges as a promising option for the future, with potential operational cost savings. Additionally, the study highlights the significance of land connections for port operations, with power shortage identified as an area of concern in some instances.

5.2. Present production sites, bunkering and charging facilities

5.2.1 Energy demand - ships calling Swedish ports

Port call statistics (PCS) for all ships arriving and departing at Swedish ports were collated for 2022 (Swedish Maritime Administration, 2023). The ships are categorized according to the International Maritime Organization’s (IMO) 4th GHG report (Faber et al. 2020) based on their size and type as provided in the PCS and further harmonized with ship parameters found in the Sea web's ship registry (S&P Global, 2024).

The ships analysed here are > 300 GT in size and include those transporting goods, such as tanker, bulk, container, RoRo, vehicle carriers and general cargo ships, as well as those moving people such as cruise ships and combined goods and passenger transportation with RoPax. The energy usages of many smaller vessels are not included in this analysis, such as fishing vessels, road ferries, public transport, small working vessels such as pilot boats, pleasure boats, tugs, dredgers, and bunker ships. Also, ice breakers have not been included in the PCS. Assigning 'home' ports to many of these, especially, smaller vessels, e.g., pleasure craft, is not feasible and would introduce more difficulties for port-based analyses. While the inclusion of such ships would provide a more holistic overview of Swedish fleet energy usage, the impact of such vessels is not expected to be significant on a national scale and would be better investigated as separate cases, which is beyond the scope of this project.

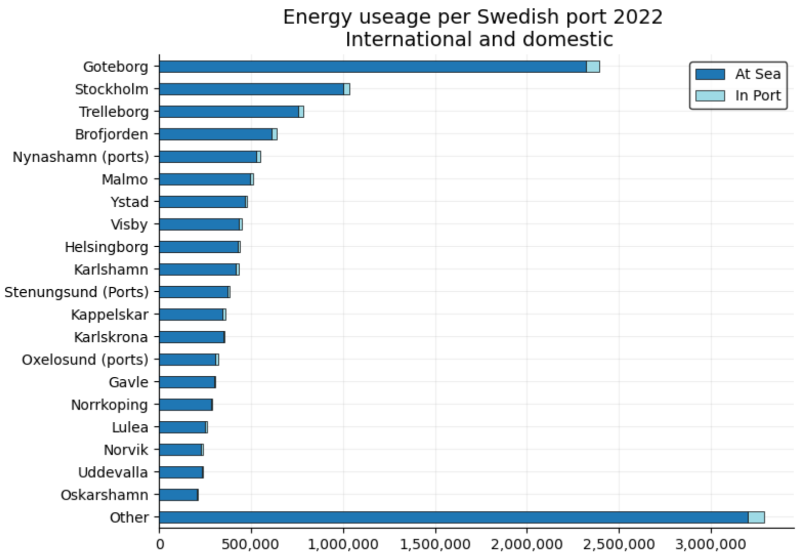
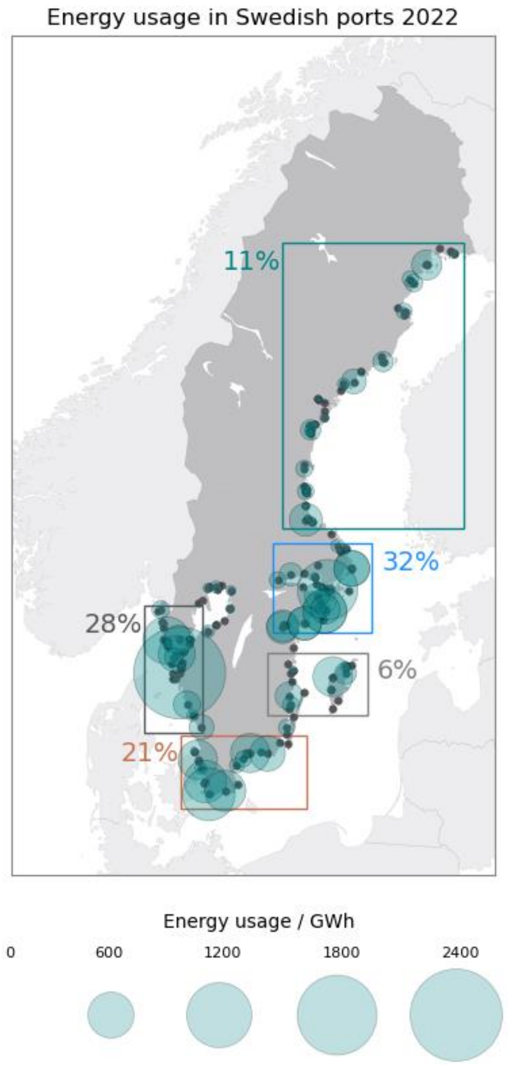


Figure 34. Energy need the 20 ports in Sweden with highest consuming ship related activities split by energy use in port and at sea for the year 2022.

The total energy used by ships visiting Swedish ports in 2022 was 14.0 TWh including domestic and international shipping. An average of 7% total energy usage was consumed in the port and the remaining 93% consumed at sea. The top twenty highest energy demanding ports consumed just over three quarters (76%) of this total, with the remaining Swedish ports consuming the remaining 24% (see Figure 34). Within the top 20 ports, between 5 and 11 % of total energy consumption was in the port itself with the remaining consumed at sea. On a per port basis, Gothenburg consumed the greatest fraction of that energy (17.1%), followed by Stockholm with just under half that value (7.4%), then Trelleborg (5.6%).



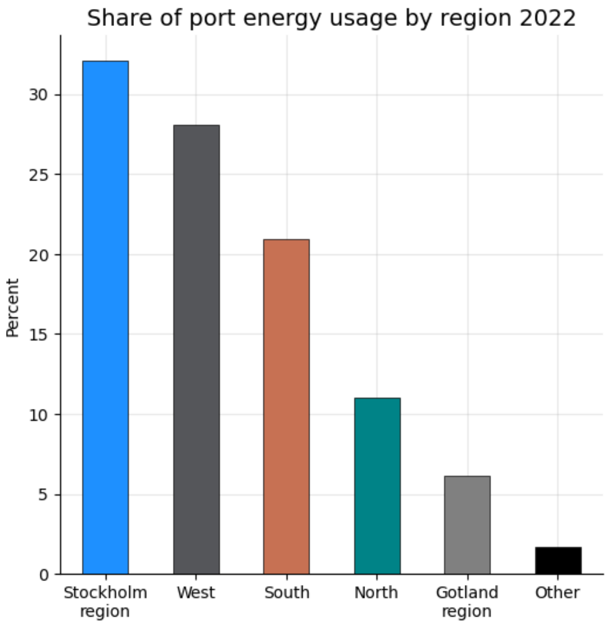


Figure 35. (a) Map of Swedish port energy usage 2022. Coloured boxes indicate regions of interest: the Stockholm region refers to Stockholm and its surrounding area, West refers to Gothenburg and the west coast, North refers to the ports on the east coast above Stockholm, Gotland refers to Visby and Oskarshamn, and South refers to Skåne, Halland and Blekinge. Percentages shown next to the boxes indicate the share of port energy usage within that region. (b) Percentage share of total Swedish port energy usage for 2022 by clustered region. Bar colours refer to coloured boxes in figure (a).

Port energy usage clusters into geographical regions of high activity, highlighted in Figure 35. The most significant of these are: the region of Stockholm, extending southwards into Södermanland and westwards inland; the west coast including Gothenburg; and the South including Halland, Skåne and Blekinge. Ports within these regions account for 32%, 28% and 21% of total energy usage respectively (see Figure 35). This indicates that while Gothenburg is the largest energy consumer on an individual port basis, the Stockholm region is actually greater when considering ports beyond Stockholm itself, albeit over a larger geographical area. Additionally, Oskarshamn and Visby on the island of Gotland are prominent on the east coast and account for 6% of total energy use. At latitudes higher than Kapellskär in the North of Stockholm County, port energy usage is significantly lower; Gävle and Luleå are the only ports above this latitude found in the top 20. When these ports are combined into their own North region, energy demand is 11% of the total.

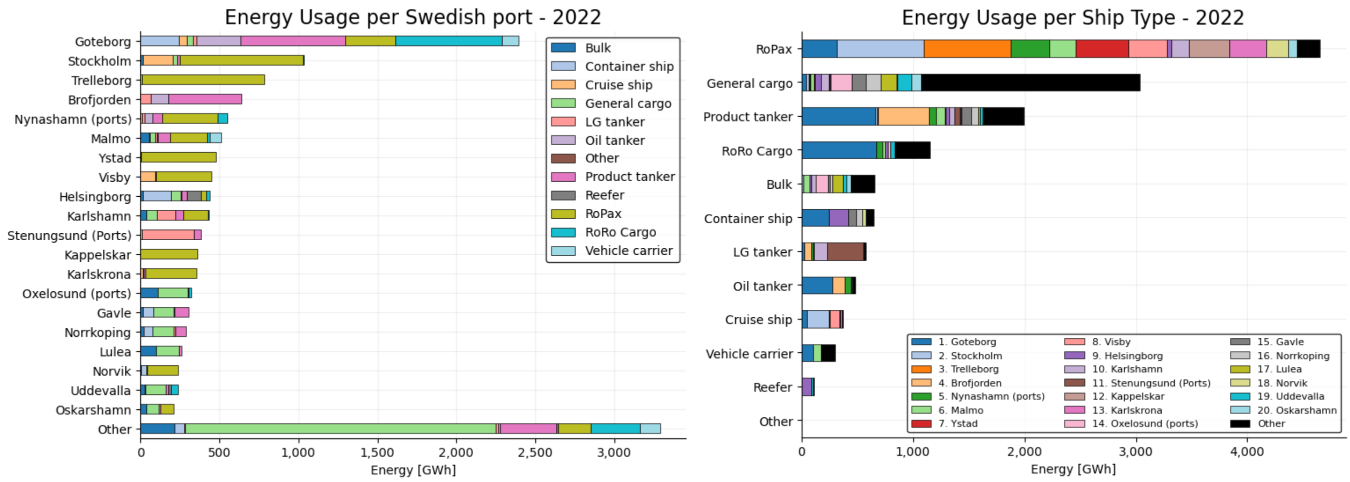


Figure 36. Energy demand for the 20 highest energy using ports in Sweden 2022 split by (a) highest energy demanding ports and (b) ship category.

Many ports in the top 20 are dominated by traffic of one specific ship type (Figure 36 a). In some instances, this dominance is nearly exclusive. For most ports, the dominant ship type is RoPax, as is the case for Stockholm, Trelleborg, Nynäshamn, Malmö, Ystad, Visby, Kappelskär, Karlskrona and Norvik. RoPax vessels are responsible for a third (33%) of the total energy usage of any vessel type and are associated with only a few, ports such as Trelleborg, Stockholm and Ystad, all of which have high energy demand (Figure 36 b).

In contrast, the next largest category of general cargo ships (22%) are more likely to call at a greater number of less energy demanding ports that are not found in the top 20. General cargo ships dominate the port calls at Oxelsund, Luleå, Uddevalla, Oskarshamn, Norrköping and Gävle, found in place 14 or higher of the top 20.

The third largest category of product tankers uses 14% of the total energy, of which half is associated with calls to Gothenburg and Brofjorden. Additionally, RoRo Cargo (8%) and oil tanker (3%) energy usage is dominated by calls to Gothenburg, whereas LG tankers (4%) are dominated by calls to Stenungsund, and Cruise ships (3%) call mostly at Stockholm.

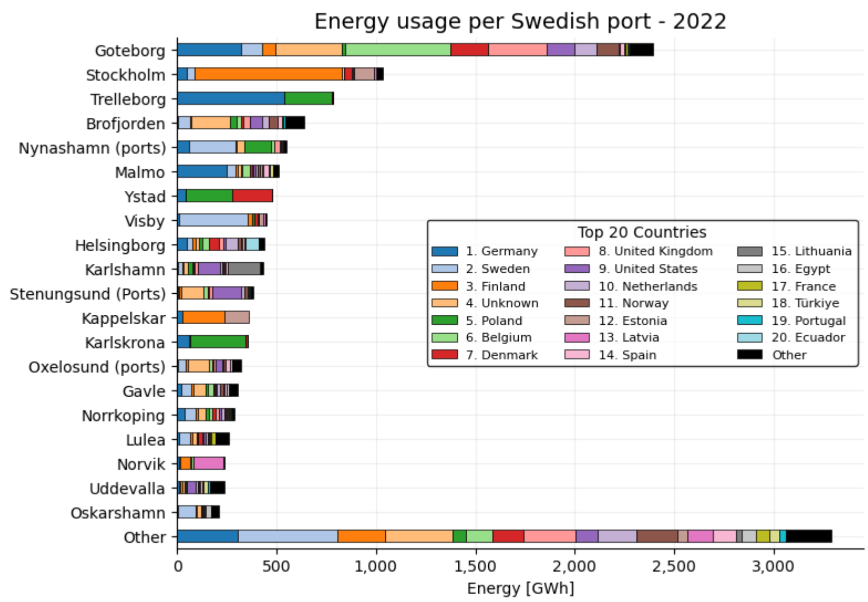


Figure 37. Energy usage for the 20 highest consuming ports in Sweden split by the 20 most common country of use in port and at sea for the year 2022.

The vast majority of energy usage concerns international shipping. 71% of energy usage at the top twenty energy demanding Swedish ports can be ascribed to port calls to or from 18 countries. Germany is the country with the highest associated energy demand (at least 13%), followed by domestic port calls in Sweden (at least 12%), and then Finland (at least 10%). The top 15 destinations are all European apart from the USA in 9th place (5%). Adding France (1%) and Portugal (0.6%), which are in 17th and 19th position in the top 20, the total contribution of European destinations to the total energy demand is at least 65% (with unknowns unaccounted for). Beyond Europe and the USA, Egypt, Turkey and Ecuador are also visible in the top 20. While 10% is unknown, the remaining 6% (Other) comprises shipping to and from 55 other countries from Northern Europe, the Mediterranean, Sub-Saharan Africa, North America, South America, East Asia, the Caribbean, the Middle East and the Indian subcontinent.

While the domestic share of total energy usage is 12%, on a per port basis only Visby, Nynäshamn, Gothenburg and Oskarshamn have domestic port calls reaching over 5% of their total energy usages. For Gothenburg specifically, ships traveling to / from the neighbouring countries of Belgium, Germany, the U.K. and Denmark are most prominent, comprising over half (55%) of all energy consumption to and from the port. Including Sweden and further neighbouring countries of Norway, the Netherlands, Finland and Poland, this increases to over two thirds of the total (69%).

5.2.2 Charging facilities and production sites

The capability to connect to landside electricity supplies for charging of vessels is available in 11 of 52 Swedish public ports, which the overwhelming majority is tailored for RoPax vessels (84%) and RoRo vessels (5%) with the remaining 11% for General cargo. Only Stockholm and Norvik, have capacity for charging general cargo. Regional analysis shows the *Stockholm region* have the greatest capacity, providing electricity at almost 20 berths including Nynäshamn, Kappelskär and Nordvik, followed by the *South region*, due to contributions from multiple ports, for examples Helsingborg, Trelleborg, Karlskrona and Ystad. Within the North region, Umeå, Piteå and Luleå provide an electrical connection.

Not shown here is the expected additional 2 berths with 11 kV available for cruise ships in Stockholm which is due to come online in 2024. There are also prepared connection to container ships in Norvik, but not yet installed. Charging facilities available to those ships not included in this analysis. Icebreakers, service ships or pleasure craft are also not shown.

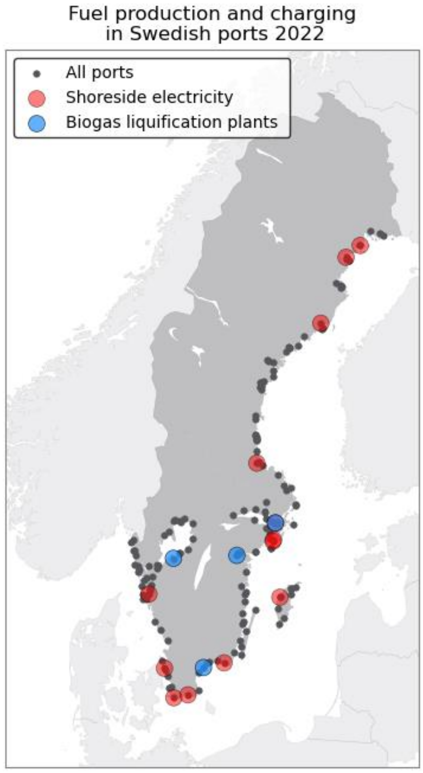


Figure 38. Fuel production and charging in Swedish ports in 2022.

There are currently four biogas liquification plants in Sweden (see Figure 38), one is found in Lidköping on the coast of lake Vänern, one is located on the south coast in Nymölla, one in Linköping, and one is located in Stockholm, which is the most northern of all facilities.

5.2.3 Bunkering of marine fuels

A large majority of bunkering activities in Sweden is performed in Port of Gothenburg or at anchor off the Swedish west coast between Gothenburg and northern Denmark. Due to limited data availability, it is difficult to identify how much, but roughly 70-80% of all bunkering in Sweden today is carried out in this geographical area. Reasons for being a busy bunkering location are the location at the gateway to the Baltic Sea, local refineries in Port of Gothenburg and several more refineries just north of Gothenburg, competitive prices and many bunker suppliers offering all the main marine fuel grades, including biofuel blends (integr8fuels, 2024).

Fuels handled in the port include MGO, marine distillate, different types of fuel oils, LNG, LBG and methanol. Approximately 1.9 million m^3 sourced from Port of Gothenburg, correspond to roughly 19 Twh, including around 2 500 bunker operations yearly (Port of Gothenburg, 2024). Additional volumes are sourced from other places to this area.

Bunkering in other geographical areas in Sweden other than the west coast, including foremost bunkering of timetable-based shuttle services between two ports, including domestic services. Examples of shipping segments bunkering outside the Gothenburg area are the ferry traffic between Gotland and Swedish mainland, the RoPax ferry operations between Finland and Sweden etc.

5.3. Technological developments

Which renewable and low-carbon marine fuels are relevant for commercialisation at different points in time will depend on the technological development and maturity of the considered technologies. Figure 39 outlines expected technological maturely development based on the results and information presented in *Chapter 3 Low-carbon shipping.* Predictions of the technological development of renewables and low-carbon fuels and propulsion technologies are not certain and affected by initiatives, early movers, regulatory development, public perception and more. Figure 39 should therefore be considered as one possible development route. Fuel production and availability considers the conditions of the Swedish market. Bunkering primarily considers technology and conditions in port. By 2040, most technologies are expected to have reached maturity if they have had continued financial and regulatory support. Continuous innovation in fuel production technologies, such as electrolysis for hydrogen production or advanced biofuel production methods, can significantly influence future demand patterns.

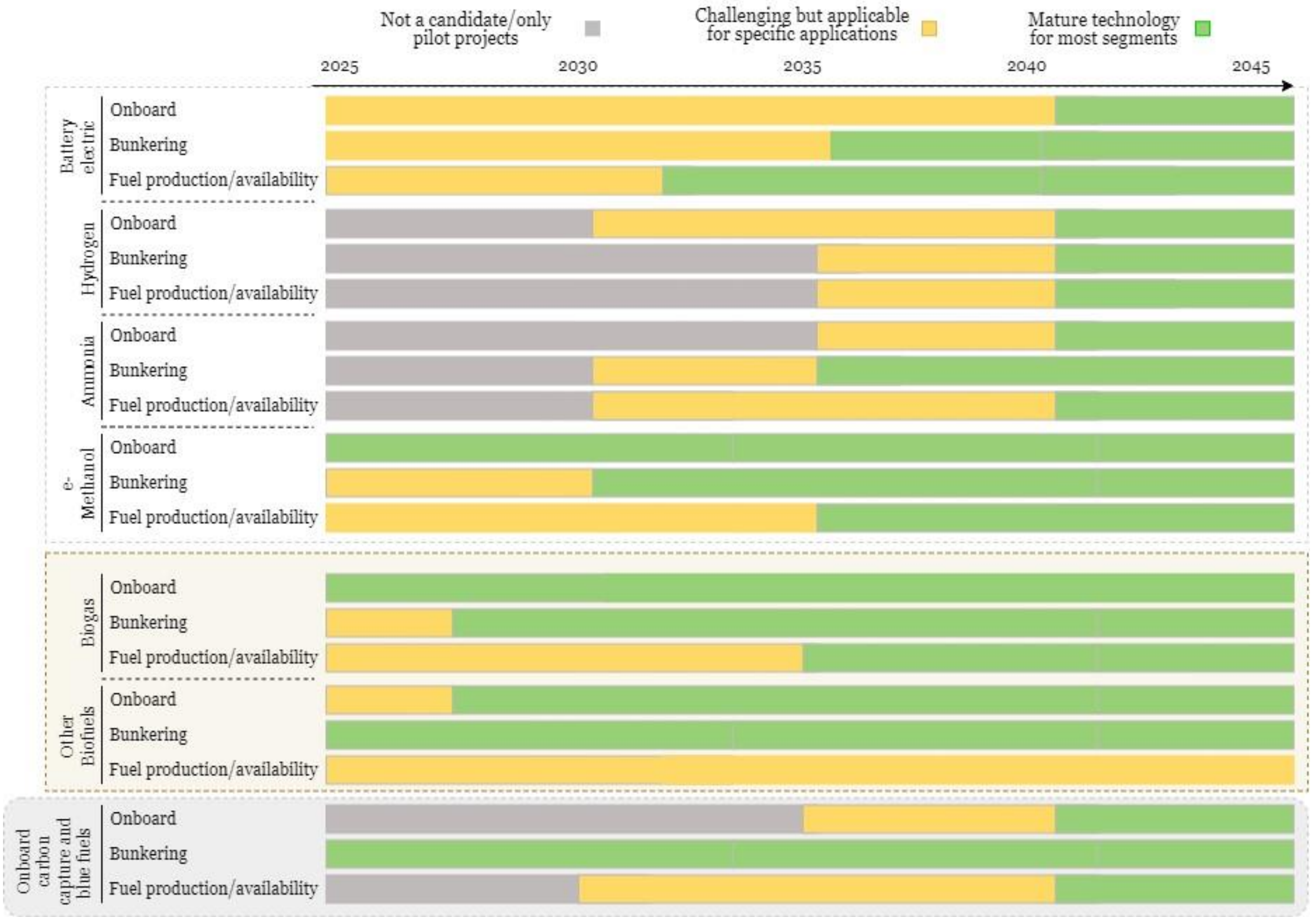


Figure 39. Possible technological development for low-carbon shipping alternative based.

5.4. Future demand for production sites, bunkering and charging facilities

The development of future demand is difficult to predict as it is influenced by many factors as well as interlinked behavior and diverse goals from multiple stakeholders. On the national level, only some general aspects can be concluded as the local conditions are crucial to the different developments and singular stakeholder initiatives creates demand at scale. If we look at the future demand at Swedish national scale and the target year of 2035, the Swedish energy administration currently expects the fuel bunker demand in Sweden to remain the same until 2035. We therefore expect no increase in demand, but the production and bunkering pattern might change.

The first step in mapping future production is to assess local production conditions. Factors such as proximity to renewable energy sources, existing infrastructure, and regulatory frameworks play pivotal roles. Renewable energy potential, including solar, wind, and tidal resources, should be evaluated to determine the feasibility of establishing production sites. Furthermore, access to raw materials for biofuel production or renewable electricity for hydrogen production must be considered. Renewable energy potential, existing infrastructure, and resource availability emerge as critical factors influencing the spatial distribution and scale of future facilities. Table 3 and Table 4 present some planned production identified today. These lists are not extensive, but we can note that the discussed production sites are of a different type where renewable fuel production connected to access to raw material is in focus. The current demand presented in *Chapter 5.2.3 Bunkering of marine fuels* shows how the main port of bunkering today is Port of Gothenburg. With increased local production, there is potential for more ports to become nodes for fuel bunkering to eliminate the need to transport fuels. The expected development of production facilities is currently fastmoving and uncertain, as market development and regulatory processes (such as permit processes) directly affect which initiatives will be put in production and economically viable at scale. To draw any direct conclusions, a more detailed analysis is required at the local perspective to take into consideration the local conditions and the drivers of local actors.

There are 11 identified ports with onshore charging capabilities today which are distributed fairly evenly around the coastline. The development of onshore electricity is expected to be driven by introduction of legislative requirements. Figure 40 shows the potential development of charging up to 2035. By 2035, it is expected that in addition to those ports already with charging facilities, TEN-T ports will also have charging facilities. This increases the number of ports with such facilities from 11 to 26. The majority on these ports are in the southern half of the country, with Sundsvall as the only northern port expected to have new charging facilities by 2035. This is due to the Alternative Fuels Infrastructure Regulation (AFIR) which dictates that TEN-T ports are required to provide charging if they have (i) more than 25 calls by passenger ships over 5 000 GT, (ii) more than 100 calls by containers over 5 000 GT, or (ii) over 40 calls by RoRo or high-speed passenger ships over GT per year. However, ports with existing onshore power supply might also need to install new connections at specific berths to meet new regulations. We have not in this report analysed which Swedish Ten-T ports would today meet these requirements. Increased demand from customers could lead to more ports installing onshore power at berths than what is presented in Figure 40.

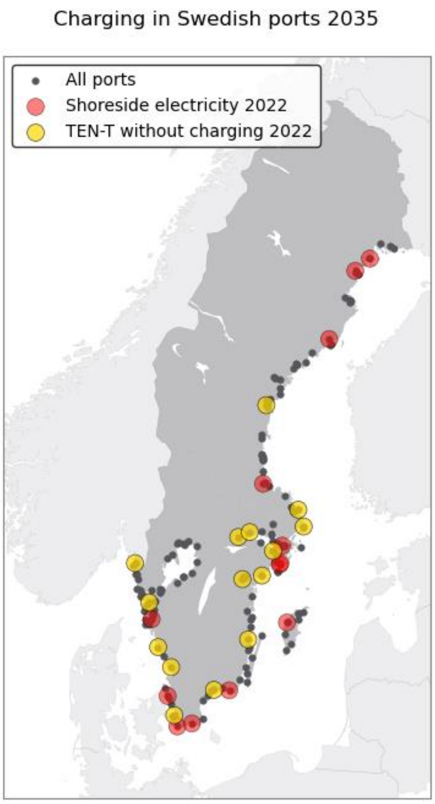


Figure 40. Potential development of fuel production and charging in Swedish ports towards 2035.

The regulatory landscape is under development, but it is likely that local production of renewable fuels will be beneficial and increase. *Chapter 3.4 Development over time* shows how the adaption of alternative fuels are ongoing in the maritime sector, but also how the speed of the adoption currently is low. Introduction of legislation is expected to be the primary driver for introduction of biofuels and electrofuels in the Swedish shipping sector. However, stronger legislation is required to speed up the adoption.

Mapping future demand for marine fuel production sites, bunkering, and charging facilities requires a multi-dimensional approach that integrates local context, stakeholder engagement, legislative frameworks, and various other relevant considerations. These initiatives may have been taken by different actors, e.g., energy companies (local, national, or international), ports and investment companies. However, we propose a general approach for how to map the demand and show a general outline of some expected developments.

A detailed mapping should include the steps described in *6.2 Guidelines for development of national/regional bunkering and charging strategy* (Step 4).

5.5. Pathway exploration, actor involvement and outline potential measures

When the mapping of future demand for production sites, bunkering and charging facilities is conducted the next step is to analyse different pathways toward realization. The main questions are: Which pathways will be relevant? What is the likely chain of events in the different options? In general, this type of assessment should include development of one or several scenarios for how to meet the potential need for bunkering and charging in a country/region/port based on ship calls, ships prerequisites and green corridors initiatives and similar actions. Such an assessment for a specific port could consider maturity level, economy, environmental impact, potential customers, local conditions (including e.g., local supply of feedstock) etc. The selection of technologies should be discussed with several actors. Forecasted predictions can only be considered possible route of development and the future might look different. It is therefore important to explore several routes and identify potential key stakeholders for the different pathways.

A detailed analysis at national scale is outside the scope of this project, as we believe this to be best conducted at the regional scale where actors can be identified and supported at a more detailed scale. However, some future outlines can be discussed. For example, the increased charging in Swedish ports should be supplied by renewable electricity and infrastructure in the port as well as in the local/regional power grip must support increased use.

Which actors in the stakeholder landscape (for the national level mapped in *Chapter 1.2 Stakeholder landscape*) should be involved in the pathway exploration depends on the targets set. If there is an expectation that relevant actors will cooperate and/or be involved in the implementation of the strategy, this needs to be clarified at this stage. Engagement with local communities, industry stakeholders, and governmental bodies is fundamental for successful implementation. Stakeholder consultation fosters transparency, builds trust, and ensures that projects align with local needs and aspirations. In this step of the strategy drafting, incorporating feedback from stakeholders helps identify potential challenges and opportunities. If there are concerns related to environmental impact, land use, and economic benefits fosters social acceptance and promotes sustainable development they should be addressed. Moreover, involving local businesses and workforce in project planning and implementation contributes to the socio-economic development of the region. For the national level, access to renewable energy and costs are two major concerns already raised by stakeholders. There concerns cannot yet be met but are discussed.

There are several key aspects of different marine fuel pathways at the national level. The demand on a national level is in this report considered to be stabile up until 2035, with some flexibility regarding where the fuel is produced (see *Chapter 5.4 Future demand for production sites, bunkering and charging facilities*). The primary activity in Sweden will therefore be to shift the fuel supply from fuels with high greenhouse gas emissions form a life cycle perspective to those with low emissions. This will require a drastic increase in use and in production. We have throughout this report assessed the current state of marine fuels, including the types of fuels being used, their environmental impact, and existing regulations. Figure 39 shows how by 2030 only some pathways are likely to be available at scale, while by 2035 most pathways analysed could be relevant for a technological perspective if it has received the required development support/attention.

The fuel availability for the shipping sector is a key factor to the future development, and with limited feedstocks and diverse use cases where different technologies in terms of propulsion etc. are the most relevant, we see that a diverse mix of fuels at the national scale is beneficial and likely required. The limited mapping potential of production sites at the national scale leads to limitations in the analysis. However, we can conclude that there are interests in biofuels (LBG in particular), electrofuels, and electric propulsion (/when it is technical applicable). There is a direct interest in electrofuels in Sweden today, with for example initiatives at scale in electromethanol, and the feedstocks considered are primarily renewable with renewable electricity and biogenic carbon dioxide in focus.

The speed of the transition ahead is currently unknown, with the identified initiatives not currently leading to actions at the national demand scale (~25 TWh). The drivers are currently not strong enough to promote a full conversion and we need further legislation and market demands to reach the targets set by the political bodies. Streamlining permitting processes, establishing certification standards, and promoting research and development initiatives would accelerate the transition towards carbon neutral fuels. However, the conditions for fuel availability, port infrastructure etc. is expected to vary greatly between Swedish regions and ports, calling for detailed analysis at regional level as well as increased monitoring at a detailed level. Understanding potential pathways and their relevance requires a multi-dimensional approach that integrates local context, stakeholder engagement, legislative frameworks etc.

We therefore suggest regional pathway exploration tied to ports where the actors define targets and sub-targets linked to the development of charging and bunkering of renewable marine fuels in ports. These targets should ideally be in line with all relevant identified pathways. Which aspects to include are pathway dependent, but from a port perspective dialog with local shipping companies and fuel producers might lead to targets on emissions in port, available infrastructure, renewable fuel availability etc. An example case of this will be developed within the Blue Supply Chains project tied to the Port of Umeå.

5.6. Plan for realisation follow-up and evaluation of the strategy

When targets have been identified and set, the scope widened to include the greater landscape and how to achieve the target. As the primary pathways and other direct measures have been identified, the realization is now in focus. How the targets are to be achieved, responsibilities and roles, as well as how targets, policy instruments and other efforts are connected need to be described for a strategy to be successful. It must be clear how targets, and effects are to be followed up and evaluated. Targets and measures need to be anchored with the relevant actors involved.

The change in technology and business models requires collaboration and governance. The goal of the plan for realization and actor involvement is to outline responsibilities and roles for various actors linked to specific ports. It is important that the process includes to move from targets/overall measures to concrete actions. Decisions need to be anchored and responsibility given to the relevant actors involved in each part of the chain. A key aspect is also to agree on a timeline for implementation of measures and to reach set targets. The plan for realization remains uncertain at the national level as the scope of pathways is not yet fully explored. However, regulatory frameworks should provide clarity and consistency to investors and industry stakeholders as this is currently seen as a barrier by the stakeholders.

5.7. Follow-up and evaluation of the progress of the strategy

It is essential to follow-up and evaluate the process of the set targets and measures. Follow-up and evaluation provide opportunities for learning and improvement. By analyzing what works and what doesn't, decision-makers can gather insights for future planning and strategy development. It allows for the identification of best practices and lessons learned that can be applied in similar contexts.

National strategies often need to be flexible and adaptable to changing circumstances such as economic conditions, technological advancements, or societal shifts. Regular evaluation helps in identifying emerging issues and ensures that the national strategy remains relevant and sustainable over the long term. By monitoring progress and adapting to changing circumstances, the strategy can evolve to meet the evolving needs of society. Establish mechanisms for monitoring the implementation of the pathway and evaluating its effectiveness in achieving the defined objectives. Regularly review progress, gather feedback from stakeholders, and adjust as necessary to stay on course towards a sustainable future for marine fuels.

How targets and effects are to be followed up and evaluated and which actor/s that are responsible for that need to be settled both for the national strategy as well as at port level. Evaluation allows for the assessment of whether the strategies and actions outlined in the national plan are achieving their intended objectives. If certain approaches are not proving effective, adjustments can be made to improve outcomes. Market trends, such as fluctuations in fuel prices, evolving consumer preferences, and geopolitical factors, must be monitored to anticipate shifts in demand and adjust the targets and the approach accordingly.

As part of the follow-up an updated mapping of infrastructure for charging and bunkering of renewable fuels in Swedish ports need to be performed as the area is under development. Regular updates on the progress of a national strategy help maintain public confidence and support. By evaluating progress, decision-makers can determine whether resources (financial, human, and material) are being allocated appropriately and efficiently.

The shift towards sustainable marine fuels necessitates a thorough understanding of various influencing factors, including local contexts, stakeholder engagements, regulatory environments, and technological advancements. However, regardless of approach, fuel production is difficult to forecast and impossible to predict. This report outlines one possible future scenario or picture of the landscape for future renewable fuels in the Swedish maritime sector, but the future might differentiate significantly from what is presented here.

6. Guidelines for low-carbon shipping

This chapter include a brief description of guidelines for 1) *low-carbon shipping on inland waterways*, and 2) *a strategy for bunkering and charging of ships in ports for a specific country or region*. The purpose of these guidelines is to provide a roadmap for stakeholders in shipping to move towards low-carbon operations and contribute to the necessary reduction of ship and port emissions.

6.1. Guidelines for development of emission free inland waterways

The guidelines for low-carbon shipping on inland waterways represent a comprehensive framework aimed at reducing the carbon footprint associated with inland water transportation. Our primary objective is to establish clear directives and best practices to promote sustainable shipping practices while leveraging the unique advantages of inland waterways.

The purpose of these guidelines is to provide a roadmap for stakeholders involved in inland water transportation to go to towards low-carbon operations. By aligning strategies and implementing innovative solutions, we aim to reduce environmental impact, enhance operational efficiency, and encourage a culture of sustainability within the inland shipping industry.

The key components for guidelines

Carbon Reduction Strategy for reducing carbon emissions along inland waterways. This includes optimizing vessel design, propulsion systems, and operational practices to minimize fuel consumption and emissions output.

Technological Innovations exploring emerging technologies such as electric propulsion, hydrogen fuel cells, and hybrid power systems to support the transition towards low-carbon shipping.

Infrastructure Development to inland waterway infrastructure to accommodate low-carbon vessels and to adapt their efficient operation. This will involve the construction of charging stations, modernisation locks and berths, and implementing digital navigation systems to optimize routes and reduce energy demand.

Regulatory Compliance to address regulatory frameworks and emission standards applicable to inland water transportation.

Stakeholder Engagement, a collaboration among industry stakeholders, including ship operators, private businesses, port authorities, government authorities, and environmental organizations, will be essential for the successful implementation of low-carbon shipping initiatives. Collaborative partnerships and knowledge sharing to make action and foster innovation.

Inland water transportation plays very important role offering a cost-effective and environmentally more sustainable comparing to traditional modes of transport. Stakeholders can implement sustainable practices that not only reduce emissions but also enhance the long-term viability and resilience of inland water transportation networks.

6.2. Guidelines for development of national/regional bunkering and charging strategy

The understanding of the transport and energy landscape is an important prerequisite for the development of a strategy for bunkering and charging of ships in ports. However, the very rapid development, lack of public data, and complexity of actors involved can make it difficult to capture all aspects. In terms of plans, many ports and other actors are investigating the possibility of producing and providing low-carbon fuels and charging facilities for ships, trucks and terminal equipment. Some actors share their plan publicly while others do not openly communicate their plans. It is difficult to predict which plans and projects that, actually, will be realized in the short- and long-term perspective. In Sweden, there is also a long and complicated permit processes for new facilities that can hinder, or delay, initiatives linked to fuel and energy production.

Based on our experiences in the Blue Supply Chains project, the following steps are suggested to develop a national or regional bunkering and charging strategy for ports, illustrated in Figure 41 and described below.

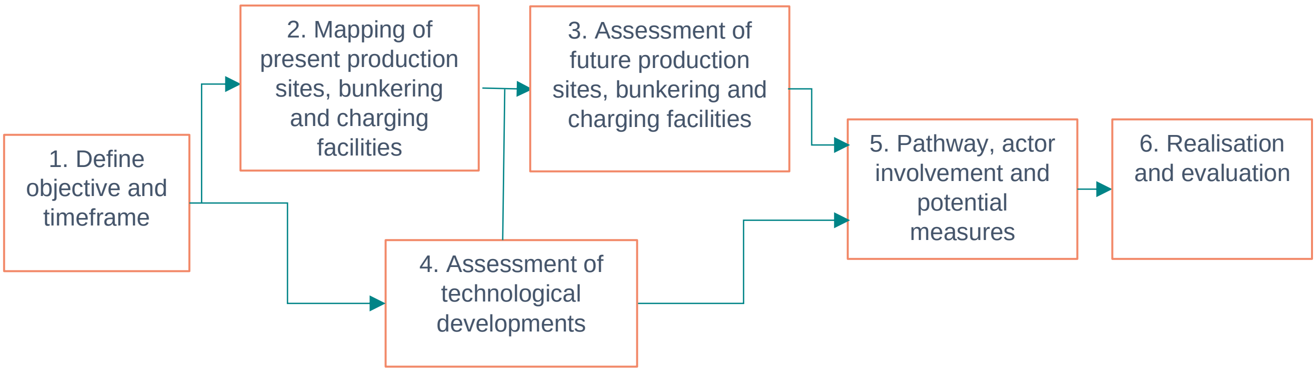


Figure 41. Schematic overview of methodology for development of national/regional bunkering and charging strategy.

1. **Define objective and timeframe of the strategy**. Set the scene by formulating and agreeing on an objective of the strategy for bunkering and charging for the relevant region/country, including the timeframe, i.e, what year the strategy will be realised.

2. **Current situation – mapping of present fuel production sites, bunkering and charging facilities** will increase the knowledge of the present energy system for maritime transport, including production of different fuels, how and where these are produced, distributed, and bunkered, and which ports that provide charging facilities and onshore power supply for ships within the geographical area selected. These tasks include:
   - Analysis of ship call data (e.g., AIS-data) to better understand number, composition and type of ships and services (e.g., liner shipping, spot market, etc.) calling the relevant ports, and the shipping services' connection to other geographical locations,
   - Identification of main fuel production sites of fuels, port facilities for bunkering and charging, bunkering locations, type of bunkering (i.e., ship-to-ship, truck-to-ship, pipeline) and bunkering patterns today, based on interviews, reports, and statistics.

3. **Assessment of technological developments** to increase the understanding of the potential for different renewable marine fuels, and related bunkering and charging infrastructure. To understand the conditions and maturity of the different fuel and propulsion options, the infrastructure and storage need of different fuels, as well as the techno-economic, environmental and safety prerequisites for various options are key information needed to be able to identify potential solutions for a specific country or region based on local conditions. It also increases the knowledge around solutions among key actors. The rapid development in this area also calls for such assessments to be updated regularly. This step includes to review aspects for the relevant fuel and propulsion options:
   - Technical performance and maturity level,
   - Infrastructure and storage needs,
   - Techno-economic assessments,
   - Environmental aspects
   - Safety aspects

4. **Plans and initiatives – assessment of future production sites, bunkering and charging facilities** include, with a starting point in current situation (Step 2), to investigate potential future production sites, bunkering and charging facilities, both planned and under construction. These initiatives may have been taken by different actors, e.g., energy companies (local, national, or international), ports and investment companies. Further, legal requirement that will affect the development need to be included in the analysis, e.g., requirements for onshore power supply and increased share of biofuels in shipping. This step include:
   - Analysis of how present ship call data (Step 2) is likely to develop until the target year for the analysis.

- Assessment of present and future initiatives for fuel production, development of onshore power supply and plans for green shipping corridors based on interviews, reports, and statistics.
- Investigation of time frame for realization of these initiatives, since this can differ greatly between countries and regions depending on legal systems and permitting processes.
- Analysis how policies and regulations (e.g., FuelEU Maritime and AFIR but also national policies) will affect the development for bunkering, charging and renewable marine fuel demand.
- Clarify the prerequisites for a specific country or region to produce and offer bunkering of renewable fuels for the shipping industries.

5. **Pathway exploration, actor involvement and outline potential measures**, includes assessment of potential pathways, actors to be involved, the outlining of overall targets or measures. This assessment could be performed both on an overall national level, but also in more detail on a port level, and includes:
   - Development of one or several scenarios for the potential demand for bunkering and charging in a country/region/port based on ship calls, ships prerequisites and green corridors initiatives and similar initiatives. Such an assessment for a specific port could consider maturity level, economy, environmental impact, potential customers, local conditions (including e.g., local supply of feedstock) etc. The selection of technologies needs to be discussed with several actors.
   - Selection of key ports for more detailed assessments to a) cover major ports, and b) specific initiatives (in Sweden for examples Destination Gotland, Wasaline, Stena Line).
   - Define specific targets and/or outline measures linked to the development of charging and bunkering of renewable marine fuels in specific ports. How the targets, policy instruments and other efforts are connected should be described.
   - Clarify which actors that need to be involved in the implementation of the strategy, based on a mapping of the stakeholder landscape. Targets and measures need to be anchored with the relevant actors involved.
   - Outline responsibilities and roles for various actors linked to specific ports.
   - In the port specific assessments also potential interaction/synergies with other industry, fuel consumers and users of port terminal equipment close to the port areas need to be mapped.

6. **Plan for realisation, follow-up and evaluation of the strategy**, includes to outline actions, to follow and evaluate the implementation of the national/regional strategy. It is important that the process moves from targets and overall measures to concrete actions. Decisions need to be anchored and responsibility given to the relevant actors involved in each part of the chain. How targets and effects are to be followed up and evaluated and which actor/s that are responsible for that need to be settled.

7. Conclusions and way forward

This report has described some important driving forces and enablers for the development of low-carbon marine fuels, but also has stressed difficulties that remain, such as high production costs, insufficient fuel production capacity, and technical immaturity and slow implementation of regulations. The fact that more than 99% of the world fleet is running on conventional fossil fuels, in combination with still too few ships with alterative solutions in the order books and long life of the ships, means that the uptake of renewable fuels will be challenging.

This report also gives directives and best practices to promote sustainable shipping, including *1) Guidelines for low-carbon shipping on inland waterways* and *2) A strategy for bunkering and charging of ships in ports for a specific country or region*. The purpose of these guidelines is to provide a roadmap for stakeholders in shipping, inland water transportation, ports, energy providers, authorities and other involved stakeholders, to move towards low-carbon operations and contribute to the necessary reduction of ship and port emissions.

The study on low-carbon shipping on inland waterways demonstrates its technical feasibility and indicates that key stakeholders are interested in adopting this shipping method. However, significant investments are required for further development, and adequate time is necessary for all potential stakeholders to integrate these new innovations into their logistics operations.

The strategy for bunkering and charging of ships in Swedish ports aims to facilitate the use of renewable low-carbon marine fuels in Swedish ports. Energy companies in Sweden are primarily focusing on methanol production for the shipping sector, with potential for a shift towards ammonia in the future. Shipping companies are focusing on energy efficiency measures and exploring alternatives such as LNG and LBG (Liquefied Biogas) to reduce emissions, while the renewable fuels are mainly discussed without concrete measures in the present. Eleven ports in Sweden have onshore power supply, and a few ports offer varying degrees of LNG bunkering activity. The majority of bunkering activities in Sweden, approximately 70-80%, occur in the Port of Gothenburg or off the west coast. This may change in the future with more local fuel production in other parts of the country.

The authors of this report would like to highlight the following conclusions:

1. **Several fuels and solutions will be available in the future and complement each other**. It is not possible to answer which fuel is best, many fuels are probably needed. There is no silver bullet like once upon a time when we switched to oil. Different solutions fit different shipping segments, ships, and sea routes. Shorter distances and smaller ships with high-frequent port calls (e.g., barges for inland waterways) are suitable for full electrifications, while large ships require liquified fuels or gases. Some shipping companies have decided which fuels to go for, but most are not yet sure and are waiting for further development. Regional availability of fuels will probably affect the choice for ships that operate in a geographically limited area. The time to market also differ between the different fuels.

2. **Ships' emissions need to be greatly reduced – now!** Although shipping is efficient in terms of energy per transported volume or tonne, the industry accounts for 3% of global greenhouse gas emissions. Further, this share is expected to increase due to increased trade and economic activities resulting in growth in freight volumes, destinations served, and overall market size. This expansion will lead to increased pressure on the environment, if not renewable fuels are introduced faster to a greater extent along with other initiatives for energy efficient shipping. It takes time to build up fuel production, infrastructure and a fleet, and this development cannot be further postponed.

3. **From centralised to more local production and bunkering, with synergies/competition between shipping and land-based industries.** Today bunkering operations are in general centralized to few ports or bunkering areas. But with increased local production, there is potential for more ports to become energy nodes. The expected development of production facilities is currently fastmoving and uncertain, as market development and regulatory processes directly affect which initiative will be realized and economically viable at scale. The need for green energy for land-based industries, increases the energy companies' customer

base and reduces the risks of building up production capacity, but also means that the shipping industry compete with other industries who want to buy the fuels. Historically, shipping has not shown the highest willingness to pay for green solutions, but this may change with new regulations and increased customer demand.

4. **Policies and regulations are required for supporting development of renewable fuels and reducing ship emissions.** There is a great focus on greenhouse gas in discussed regulations, but damaging emissions and contaminants to water, local air pollutants and biodiversity impacts are also key aspects to consider for production and usage of sustainable marine fuels. The most common emissions besides GHGs include nitrogen oxides (NO_X), sulfur oxides (SO_X), and particulate matter (PM).

5. **Pilot project and financial support needed to prepare for full scale transformation.** The shift requires large investments for the industry and society, and the costs need to be shared. This includes initiatives such as maritime policies, regulations, funding programs, from IMO, EU, authorities and governmental or quasi-governmental bodies.

6. **All costs in the complete supply chain need to be pushed down for renewable fuels to be competitive.** The analysis in this report shows that the cost of renewable fuels is high, and both demand and supply are very difficult to estimate. Economies of scale and better technical solutions will decrease costs in the future, but the whole supply chain needs to be taken into consideration.

7. **Cooperation among many actors is required and increased knowledge to grasp the quick development**. Cooperation and long-term commitment are necessary to share risks, costs, and benefits of the new solutions for the shipping industry. The understanding of the transport and energy landscape is an important prerequisite. However, the very rapid development, lack of public data, and complexity of actors involved can make it difficult to capture all aspects. In any case, it is not a one-man show, but requires close cooperation over a long period of time among many actors.

8. **Business opportunities ahead**! As regulations tighten, demand for the fuels will increase while production costs are expected to decrease. Electrification and renewable fuels will create new opportunities for the actors willing to invest.

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