A Framework for Assessing the Applications of Marine Hydrogen Fuel Technology in Baltic-North Sea Region Shipping

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Abstract

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Marine transportation, specifically container ships, bulk freighters, and tankers, account for around three percent of global greenhouse gas (GHG) emissions (1). The fuels used – heavy fuel oil (HFO), distillates, and marine diesel (MDO) – provide propulsion power to vessels through combustion, which releases CO_2 and other gasses to the atmosphere, accelerating global climate change. Shipping companies are increasingly investing in dual-fuel solutions, hybrid fuels, natural gas, methanol, and ammonia to propel ships, but these fuels still rely on combustion to produce power. While GHG emissions might be reduced, they are not eliminated. The shipping industry and the International Maritime Organization (IMO) member states have acknowledged that it will take a combination of multiple fuels to achieve its goal of near net-zero GHG emissions "around, i.e. close to, 2050" (2). Hydrogen fuel cell technology has the potential to contribute to achieving this goal, especially if applications are focused on vessels operating in short-sea capacities.

Hydrogen as an alternative transportation fuel is being tested, and indeed used, in municipal bus systems and passenger vehicles, and has been considered in limited capacities in the maritime industry. Port entities and corporations have made efforts to introduce marine fuel cells for passenger ferries and tugboats. These include the Ports of Antwerp, Belgium; Vågen, Norway; Hamburg, Germany; ferry operator Norled (Norway) and startup Golden Gate Zero Emission Marine (United States). In addition to private (tugboats) and public capacities (ferries), militaries in the U.S. and Germany have implemented fuel cell technology for various types of vessels. Marine hydrogen has yet to be tested in a commercial shipping capacity yet these ships transport freight with excess capacity, make routine, frequent calls to ports, and do not require the fuel load of ocean-going ships.

This work determines the extent to which hydrogen fuel cell technology could reduce CO_2 emissions from short sea sailings (SSS) in the Baltic-North Sea region (with a focus on Nordic countries). A fuel-cycle emissions model is developed to estimate current SSS emissions using traditional fuels. Results show container ships and crude oil tankers have the highest emissions intensity, while support craft play a comparatively small role in climate change. Then, this model is applied to a range of fuel cell technologies to compare emission reductions. With higher rates of adoption, marine hydrogen can reduce emissions in the industry, independent of vessel type. Finally, the model is used to analyze specific O-D port pairings and liner (multiple, scheduled ports of call) services to determine which ports services have the greatest potential to reduce GHG emissions as a result of converting ships to hydrogen fuel cell propulsion systems. This work provides additional commentary on conditions that may influence marine hydrogen investment throughout the Baltic-North Sea region.

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DEDICATION

To Emily, Henry, and Quinn for your endless love and support.

And to John Romankiewicz whose passion inspires this work.

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Glossary of Terms

Shipping Terminology

Deep-sea shipping: Often international in nature. Vessels transport dry and wet freight over long distances and typically leave the continental shelf to do so. An example is a voyage between China and Europe, with all ports of calls in between.

ECA: Emission Control Areas

EEZ: Exclusive Economic Zone

IMO: International Maritime Organization, the UN agency responsible for governing the international maritime industry.

Inland: waterborne transportation that utilizes navigable waterways including, but not limited to canals, rivers, and lakes. The depth of water in these waterways is typically less than in maritime waterways, which results in a different set of ship designs.

Nearshore: maritime operations that occur within shipping channels or within the boundaries of a port.

Offshore: operations including oil and natural gas drilling, wind farms, research, or surveying that require transportation by waterway.

Short sea shipping (SSS): international, intranational, or regional voyages that travel short distances relative to Deep-sea shipping, and whose ships rarely leave the continental shelf.

Vessel Characteristics

Draught: the draft of a ship, or the average distance between the waterline and keel. Draught is observed fore, aft, and amidship. The recorded value is the midship observation. Draft can be limited by the vessel's class (e.g., Panamax-class = 12m)

Beam: the width (m) of a ship. This measurement determines the class of a ship (e.g., Panamax-class = 32.3m)

LOA: "length overall" the is the maximum length of ship from the forward-most point of the bow to the aft-most point of the stern.

Deadweight tonnage: the weight (metric tons) of all cargo, fuel, water, and provisions on board a ship.

Lightweight tonnage: the unladen weight (metric tons) of ship without cargo, fuel, water, or provisions

Gross tonnage: the interior volume (m^3) of a ship including cargo area, crew quarters, bridge, engine room, etc.

Net tonnage: the interior volume (m^3) of cargo area(s) in a ship.

Powerplant: a vessel's main engine used for propulsion power. Maximum output is generally measured in kW.

Emissions Models
LCA: Life cycle analysis

LCC: Lifecycle cost

LCE: Life cycle emissions

FCE: Fuel cycle emissions

Marine Fuels
LNG: Liquefied natural gas

LPG: Liquified petroleum gas

HFO: Heavy fuel oil

MDO: Marine diesel

Marine Hydrogen Technology
PEMFC: proton exchange membrane fuel cell

PAFC: phosphoric acid fuel cell

MCFC: molten carbonate fuel cells

SOFC: Solid oxide fuel cells

DMFC: Direct methanol fuel cells

Port and Country Designations
Each port is assigned a unique country UNLOCODE. The first two digits represent the country and are listed below. The next three digits represent the unique port code within the country.

BE: Belgium

DE: Germany

DK: Denmark

EE: Estonia

ES: Spain

FI: Finland

FR: France

GB: Great Britain / United Kingdom

GR: Greece

IE: Ireland

IT: Italy

LT: Lithuania

LV: Latvia

NL: Netherlands

NO: Norway

PL: Poland

PT: Portugal

RU: Russia

SE: Sweden

TR: Turkey

Chapter 1: Introduction

1.1 Marine transportation and Greenhouse gas emissions

Marine transportation, specifically freight, bulk goods, and tanker ships, account for around three percent of global greenhouse gas emissions (GHG) (1). The fuels used – heavy fuel oil (HFO), distillates, and marine diesel (MDO) – release GHG during combustion to produce power for propulsion. Various shipping companies have invested in alternative fuels and technologies to reduce GHG emissions: Maersk introduced its first of 18 Hyundai "methanol-enabled" duel fuel ship in 2023 (3), North Sea Container Line and partner Yara Clean Ammonia will introduce the world's first ammonia-powered container vessel in 2026 (4), Yara also introduced a fully battery-electric propelled container vessel in 2021 (5), and numerous vessel owners – particularly LNG tanker owners – have turned to natural gas as a lower-carbon intensity fuel to propel vessels (6).

The main problem with methanol, ammonia, and natural gas is that these fuels are still considered "drop-in," i.e., they are still combusted to provide power to propel ships and therefore emit GHGs as exhaust. Battery electric vessels can eliminate shipboard emissions, but most in the maritime industry agree it has limited capacity to scale due to the weight of current battery storage technology. The International Maritime Organization (IMO) and fleet owners have acknowledged that multiple fuel and technology paths must be pursued to reach their stated goal of "around" fifty percent reduction in GHG emissions from the shipping industry by 2050 (7). One of these fuels is hydrogen (H_2). There are four main fuel cell technologies that can be implemented in maritime applications: proton exchange membrane fuel cells (PEMFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and direct methanol fuel cells (DMFC). Each of these four uses electrochemical reactions rather than combustion to produce energy. GHG emissions, then, can be wholly eliminated.

Fuel cell technology has its limitations, however. The energy density by volume of H_2 is about half that of petroleum products (PH1). For that reason, fuel cells might not be direct replacements for MDO powerplants on ocean-going (long distance) freight vessels. They can, however, replace power plants for short-distance and "feeder" vessels that operate on or near the continental shelf. These operations are known as short sea shipping.

There are geographic areas that rely heavily on short sea shipping (SSS) for trade in addition to ocean-going traffic: The Baltic and North Seas region, the Mediterranean Sea, and the Pearl River Delta in China are notable cases. The freight industry in even smaller regions like the Puget Sound in Washington State and the Great Lakes-St. Lawrence Seaway in the United States and Canada also benefit from short-sea operations. Compared to ocean-going vessels, ships used in SSS are smaller, operate at slower speeds, make more calls to multiple ports, and are less likely to travel at capacity. These characteristics make SSS an ideal case for implementing hydrogen fuel cell propulsion systems.

This research is focused on short sea shipping emissions in the Baltic Sea, particularly covering the Nordic countries of Denmark, Norway, and Sweden. This region is one of the busiest short sea markets in the entire world in addition to various other maritime enterprises like commercial fishing, passenger transport, and energy export. Based on traffic alone, the Baltic Sea serves as an excellent test case for evaluating the potential of H_2 to reduce maritime emissions. Based on recent experiences, though, the Baltic Sea and the countries surrounding it is a logical location for H_2 to be tested soon. Norway is home to the world's first hydrogen-powered ferry. Various Nordic companies are on the forefront of developing alternative fuel vessels including Yara and Maersk (3–5). Especially in Norway, public funding has supported the development alternative fuels, and the Danish Maritime Authority has signaled a willingness to likewise support technology development (PH2; PH3). Finally, in an effort to reduce freight emissions researchers in the Baltic have suggested SSS as an alternative to truck and rail transport (8,9). It is important to reduce road-based emissions, but just as important to reduce vessel-based emissions if climate goals are going to be met.

1.2 Research Objectives

The purpose of this study is to determine if and by how much marine hydrogen fuel cell technology can reduce maritime emissions from short-sea cargo operations in the Baltic-North Sea region. As a nascent industry adoption would occur slowly and over time. It may be necessary to prioritize future investment in a hydrogen economy in specific ports or groupings of ports. This, then, is the guiding research question of this work:

> **What are the impacts of marine hydrogen fuel cell adoption in specific Baltic-North Sea region ports?**

This question is ultimately the fourth step of the research. First, Baltic-North Sea region shipping needs to be modeled, the fleet quantified, and routes identified. Next, baseline emissions will be estimated using existing propulsion technologies (primarily MDO and HFO). Once the baseline emissions estimate is established an emissions model will be developed for the four fuel cell technologies. Finally individual ports and trade routes will be evaluated using the hydrogen model and comparing results to the baseline.

1.2.1 Research Question 1: What is Short Sea Shipping Activity in the Baltic-North Sea region?

The Baltic-North Sea region is a complex network of over 500 ports spread across 13 countries, yet short sea shipping extends even beyond this network to Western Europe and the Mediterranean Sea. Utilizing historic Automatic Identification System (AIS) vessel tracking data the SSS network will be mapped and the factors that differentiate SSS vessels from deep sea ships identified. Underlying assumptions about the feasibility of hydrogen fuel cell adoption are that SSS vessels are smaller, older, and operate with excess cargo capacity. These assumptions will be tested and presented in Chapter 3.

1.2.2 Research Question 2: What are the current Baltic-North Sea region SSS CO_2 emissions?

Chapter 4 details the development of a fuel-cycle emissions model to estimate current emissions from short-sea shipping. Current models consider maritime shipping as a homogenous group of actors. In reality, the operations of short sea vessels vary greatly from deep-sea vessel operation. Age of the vessel, shallower drafts, the practice of transporting good with excess ship capacity can make these short-sea ships less efficient than ocean-going craft. A case study of short sea vessels in the Baltic-North Sea region and is presented as proof of concept for the model.

1.2.3 Research Question 3: What are the impacts of marine fuel cell adoption on SSS emissions?
The emissions model developed in Chapter 4 will be modified for hydrogen-specific emissions factors. The emissions model will accommodate multiple fuel cell configurations to determine if, and by how much marine fuel cells can reduce emissions from today's fuels (MDO and HFO). This model will include what the literature suggests are the most easily adapted fuel cell configurations: proton exchange membrane fuel cell (PEMFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC) and direct methanol fuel cells (DMFC). Each configuration requires different feedstocks and operates at different efficiencies. Adoption will be simulated across multiple adoption scenarios ranging from 5% to 25% of SSS vessels. The findings are presented in Chapter 5.

1.2.4 Research Question 4: What are the impacts of marine fuel adoption on SSS emissions for specific ports and port pairings?
The objective described in Chapter 6 requires disaggregating the fuel cycle FCE model assumptions (carbon intensity, fuel origin, transportation emissions) from a country or regional scale down to a local scale. Ports and port pairings will be analyzed on an individual basis using the same simulation approach to highlight the portions of the network that stand to benefit most form fuel cell adoption in terms of CO_2 emissions. In addition to the quantitative outputs of the model, this chapter seeks to provide an overview of factors that can positively or negatively impact the transition to a hydrogen economy.

1.3 Contributions

Ultimately, this dissertation details the estimated impacts of hydrogen fuel cell adoption on a specific case of short sea shipping. However, each chapter contributes to the wider body of work. In Chapter 3 a replicable process for identifying and analyzing short sea traffic using publicly available data is detailed. This process can be modified or scaled to focus on different sectors: fishing, passenger transport, inland waterway activity, or port operations. Chapter 4 establishes a previously unreported emissions estimate. This estimate and similar estimates using the same process are useful to an array of stakeholders: shippers, carriers, port authorities, and policy makers. Chapter 5 develops a model and process that can be adapted for technologies beyond hydrogen: dual-fuel systems, modular nuclear, battery electric, and beyond. Finally, Chapter 6 provides commentary on the approach stakeholders should take to prioritizing the major investments required for a major energy shift.

Chapter 2: Literature Review

2.1 Introduction

Maritime freight transportation can be divided into three main segments: Deep-sea, short-sea (SSS), and inland. Deep sea shipping involves the transportation of dry (bulk, containerized, or roll-on/roll-off) and wet (liquid or gaseous) freight between international markets. Deep sea is a reference to the tendency of these vessels to travel beyond the continental shelf to complete a voyage. Short-sea vessels are also responsible for the transportation of dry and wet freight but in a more limited spatial capacity. Typically, these vessels transport goods between intranational or intraregional ports that can be reached without leaving the continental shelf. Finally, inland waterways play a major roll in the transport of certain commodities: e.g., timber, oil, coal, and construction aggregates. The extent of inland waterway transportation is limited to navigability and depth of rivers and canals and as such is limited in its scale except in certain parts of the United States and Europe.

Almost all ships in use today utilize fossil fuels to generate propulsion power. The petroleum-based fuels collectively known as "bunker fuels" include Marine Distillate Oil (MDO), Heavy Fuel Oil (HFO) and Liquid Natural Gas (LNG). The scope of this research is limited to SSS in the Baltic-North Sea region. It covers 13 countries which border those seas plus ten other European SSS destinations. MDO is the most utilized fuel in the study area due to an Emission Control Area (ECA) that covers the Baltic and North Seas to protect local ecosystems as well as population centers. HFO is commonly combusted on the open ocean where regulations are at a minimum. Natural gas is an alternative to the higher-emitting MDO and HFO but in the study area use of LNG as a propulsion fuel is limited to LNG tankers.

2.1.1 Scale and scope of maritime emissions

In Europe water transport – which includes SSS, ferries, etc. accounts for 8.4% of all petroleum products consumption (10). Figure 2-1 shows the comparison of water transport to all other sectors partially or wholly reliant on fossil fuels in the European Union.

2.1.2 Understanding Maritime Trade Patterns

Containerized maritime freight exists in two distinct spheres. One is a relatively localized hub-and-spoke system (11) and the second is ocean-going craft. The hub-and-spoke ships tend to be fairly small: 100 to 200 twenty-foot equivalent units (TEU). Owing to their relatively small size, power requirements and short, repetitive routes, these feeder-type of vessel may be the first to adopt marine fuel cells as the technology scales up from passenger ferries. The infrastructure supporting hydrogen as a fuel would be centralized around a hub such as Guangzhou or Hong Kong in the Pearl River Delta, China or Rotterdam, Netherlands in the North Sea trade region (12). The environmental benefits from these small ships converting to marine fuel cells would also be great. Hub routes are generally close to shore and large populations (32 million in the case of the Pearl River Delta) are subjected to the health risks related to ships emissions. This hub-and-spoke condition does not exist the world over, however. Ji et al (12) identifies just eleven total. Many of the largest ports, such as Long Beach and New York/New Jersey are serviced primarily by rail and drayage trucking, which present their own emissions problems to local populations. That being said, John Andrews does identify refueling hydrogen storage at major, or hub, ports as a priority in decarbonizing the shipping industry (13).

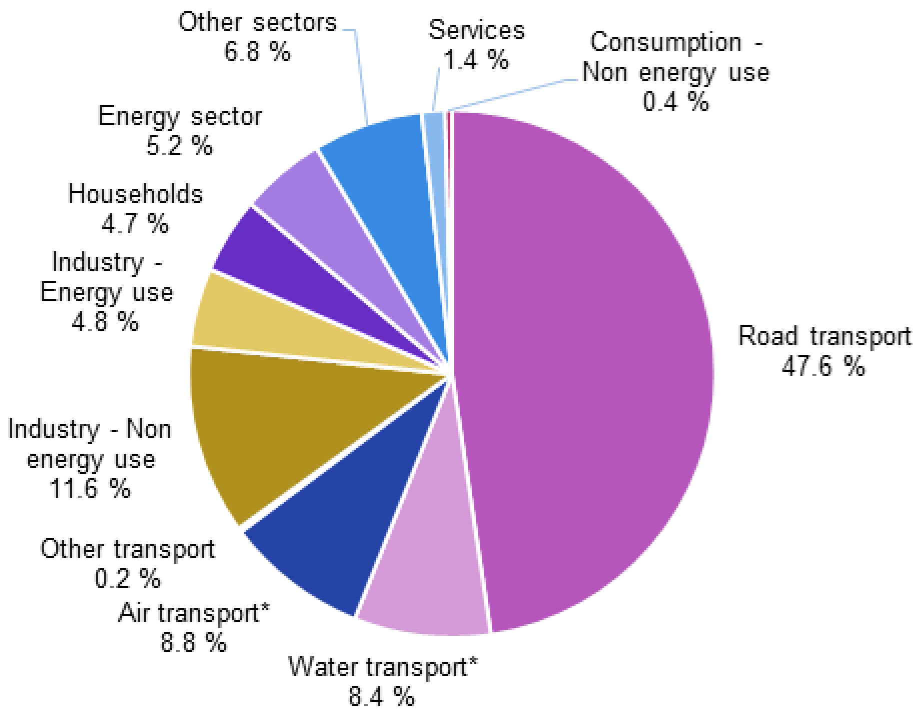


Figure 2-1. European Union consumption of oil by sector (10)

Ocean-going or liner vessels (12) can be as large as the Maersk Triple E Class, which carry almost 18,000 TEU between ports in the North Sea, Persian Gulf, and East Asia (Maersk, 2019). These ships generally travel along well established, repetitive routes to the same ports (14). They do, however, make different stops along the main routes when traveling in opposite directions. Maersk's AE6 route ships, for instance, make seven stops between Busan, South Korea and Felixstowe, United Kingdom in the westbound direction, but skip ports in Portugal and Malaysia in favor of one stop in Singapore along the eastbound route (Maersk, 2019). This type of inconsistency, governed by the nature of trade between Europe and East Asia, may pose a barrier to marine fuel cells because intermediate fueling stations would be required in ports that see roughly half the maritime traffic as the origin and destination ports. Kaluza et al's (14) 2010 study sets a good precedent for the nature of this paper in that it studied over 16,000 individual vessel routes to understand patterns of ship travel. Similar analysis is required to identify routes that can optimize hydrogen use and capital expenditures.

2.1.3 Short-sea sailings in the Baltic and North Seas

Nordic nations have particularly close relations when it comes to maritime trade.

Discussion of cabotage legislation that results in more SSS vessels (11). Similar laws exist in the United States, however they are localized rather than nationwide. A foreign flagged ship can transport U.S. goods between Los Angeles and Miami, but not from one of those ports to Puerto Rico.

2.1.4 Vessels involved in short sea operations

Ships carry a variety of goods, some of which require specialization for efficient transport. In general vessels can be split into two main categories: cargo for dry goods and self-contained liquids (e.g., barrels of food oil) and tankers for liquid and gaseous freight. These categories can be further divided by specialization. The following is the widely accepted identification of ship types. This study also considers the various support craft that are vital to the maintenance and operation of short sea shipping. These include vessels that transport consumables, materials, and crew to offshore sites as well as those vessels that assist with navigation in nearshore applications.

Dry Cargo Vessels

Bulk Carrier: used to transport grains, ores, sediments, and other loose materials.

Container: transports containerized freight is 10-foot equivalent units (TEU).

General Cargo: a flexible ship that can accommodate containerized freight, roll-on/roll-off equipment, and break-bulk materials.

Heavy Lift: ships come is various shapes and sizes but are usually used to transport large equipment either on a deck or partially submerged.

Reefer: refers to ships that are specialized to carry refrigerated or frozen materials. This cargo may or may not be containerized.

Ro-Ro: stands for "Roll-on/Roll-off." This ships specialize in vehicle, truck, and equipment transportation.

Liquid and Gaseous Goods

Bunkering tanker: used to distribute liquid and gaseous fuels to port bunkering (i.e., storage) facilities or directly refuel ships.

Chemical/Oil tanker: general purpose liquid tanker that can move crude oil, refined oil products, bituminous materials, and non-petroleum-based liquids.

Crude Oil tanker: specialty tanker used for the transport of crude oil from offshore locations or port hubs.

Floating Storage: specialty tanker that stores large quantities of crude oil at offshore sites. These ships are typically underpowered with engines used for station keeping and sea-to-shore transportation assisted by tugs.

LNG Tanker: specialty tanker used to transport cryogenically liquified natural gas products.

LPG Tanker: specialty tanker used to transport cryogenically liquified petroleum gas products or petroleum gas products in gaseous form.

Support Craft

Crew transportation: vessels used to shuttle offshore oil, wind, and gas workers to and from offshore and nearshore sites.

Dredging operations: dredging ships come in multiple forms, but their purpose is to remove sediments and debris from shipping lanes.

Offshore platforms: mobile platforms used to erect new oil and gas rigs, provide landing space for offshore helicopter support, or transport large equipment offshore. These vessels travel under their own power as opposed to tug-assisted travel by floating storage vessels.

Offshore supply and support: ships specializing in the transport of materials, equipment, and crew to offshore and nearshore sites. Some may alternatively be referred to as anchor-handling vessels.

Pilots: vessels used to provide navigation assistance to other vessels in congested or restricted waterways.

Tugboats and towing vessels: vessels that provide navigation and maneuvering support to other vessels.

2.2 Maritime Freight Emissions

2.2.1 Overall emissions and international regulation

The International Maritime Organization (IMO) has yet to adopt a regulatory framework for the reporting of emissions from ship owners. A number of studies have attempted to estimate emissions in various ways. Leonardi and Browne (2010) (15) estimates sea transport emissions from two specific supply chains: apples and furniture. While the research relies on total fuel consumption of the vessels, the metric used, gCO_2e per kilogram evaluates only the GHG emissions from a specific supply chain. The authors suggest, then, that emissions for apples can be reduced by using a direct, chartered line but ignores the fact that a shared container vessel will still be in operation with or without the apples.

Proposed emissions metrics by the IMO similarly rely on carbon intensity per unit of capacity used. This however, provides good benchmarking, taking into account empty containers and ship that are not at capacity.

2.2.2 Short-sea emissions

Medda and Trujilo (2010) (16) suggests short sea shipping (SSS) can provide a sustainable alternative to road transportation to support such trends as just-in-time shipping. But as discussed, SSS also provides valuable feeder operations to larger, ocean-going craft

Leonardi and Browne (2010) (15) explain that utilizing transshipment liners, or short-sea vessels can reduce or increase emissions of a supply chain depending on the cruising speed and draft of the vessel. While reducing the number of ports of call using these short-sea vessels decreases the time at sea and therefore fuel use, placement of the hub port in relation to the cargo's end destination is key. In this case, utilization of the hub port resulted in 12% higher emissions from ~9% higher mileage.

Short-sea voyages are more likely to occur within Sulphur Emission Control Areas (SECA) and Emission Control Areas (ECA). The United States and a number of European nations have implemented these zones in agreement with the IMO to reduce localized air pollution (17,18).

2.3 Alternative Fuels for marine applications

Ship owners and the IMO (and by inclusion, its member states) have acknowledged that reducing emissions will require a range of technologies and that perhaps some fuels will be used as stepping stones until cleaner, more efficient fuels are proven cost effective. Today's debate on the fuels of choice often revolves around ammonia or methanol, but hydrogen is increasingly seen by researchers as viable (19).

Recent investment has focused on "dual-fuel" vessels that can combust methanol in addition to traditional marine fuels (20). Cargill and Maersk, major carriers in the dry bulk and container industries, respectively, have both introduced "dual-fuel" vessels in the last three years (21). The World Shipping Council estimates that since 2021 around 400 duel-fuel ships have been delivered to date with orders for future vessels exceeding 700 (22). Bunkering of methanol is possible using existing infrastructure, but the production of the fuel is energy intensive.

Hydrogen is a combustible material, but it has not been widely tested as a combustion fuel for marine propulsion. A recent study demonstrated the efficacy of H_2 as fuel for a typical 2-stroke marine engine (23). The main issues are the injection rate – it was difficult to achieve efficient injection of H_2 at high RPMs necessary for accelerating to cruising speed – and NO_x emissions (23). Hydrogen produces up to 49% more NO_x emissions than diesel owing to the higher combustion temperature (23). One major technological hurdle is the potential of H_2 to embrittle traditional fuel systems and engine components (24). Unlike natural gas, methane, and ammonia, hydrogen cannot simply be used as an alternative drop-in fuel. Rather, substantial upgrades are required.

2.4 Why (or why not) hydrogen?

Numerous studies suggest fuel cell technology is being outpaced by bio-based fuels like methanol, ammonia, and ethanol (25). Fuel cells do, however, provide benefits over these types of fuels. Foremost is the fact that biofuels with the proper feedstock have lower lifecycle emissions that bunker fuels or heavy fuel oil, are still combusted and therefore emit CO_2. Fuel cells eliminate combustion altogether and therefore emissions come only from the hydrogen feedstock (26). Fuels cells also have the capacity to produce power (propulsion and shipboard power) more efficiently than internal combustion engines (ICE) (26,27).

When ship owners and shipping companies discuss alternative fuels, they typically mean fuels used for propulsion, the bulk of energy consumption on-board a vessel. Research suggests, however that hydrogen can be introduced to the shipping industry for auxiliary services included distributed electricity (for crew quarters, controls, and on-board equipment) and emergency power generation (28). Outside the avoidance of combustion emissions there are advantages to adopting hydrogen as an auxiliary power source as a first step. First is to institute safety protocols related to hydrogen storage and equipment maintenance. Crews will necessarily require training and smaller systems can act as foundational to the safety procedures for a propulsion-scale fuel cell equipment.

The International Energy Agency and some member countries have recognized the potential for hydrogen to reduce 1) reliance on fossil fuel combustion and 2) emissions related to the energy and transportation sectors (29). Investments are being made to replace fossil fuel-powered electric generators with fuel cell technology and well as the clean production of hydrogen for other uses (29).

2.4.1 Barriers to Marine Hydrogen

Hydrogen fuel faces barriers that can be categorized as related to vessels, infrastructure, hydrogen feedstock, economics, and public policy. Each has been evaluated to a certain degree by existing literature. Balcombe et al (30) outline each of these and highlight ship-related barriers by focusing on the energy content of hydrogen. They assert that liquid hydrogen would require about eight times as much space as traditional marine fuels for the same energy output (30). Ship owners would find it difficult to retrofit vessels to accommodate this need, and it may require a whole new fleet.

Infrastructure for refueling ships currently only exists for the harbor craft and ferry prototypes. Converting maritime shipping to hydrogen will require enormous capital investments in hydrogen generation, distribution, and storage. In some cases, existing natural gas infrastructure can be used (30), but only in limited ways. Ports provide ideal locations for hydrogen generation. Many natural gas import/export terminals are located at ports, and deep sea reserves are transported to major ports. This natural gas can be reformed into hydrogen instead of being burned as a transportation or electricity fuel source. Despite the capital cost barriers, many sources agree that marine hydrogen would ideally be placed in “highly developed ports with available infrastructure (e.g. Rotterdam and Tokyo)…” (30).

Perhaps the biggest barrier to marine hydrogen is the cost, which is why this study seeks to use it as the objective in an optimization problem. Balcombe et al, Andrews and Shabani, Raucci, et al and Tronstad et al all concur that hydrogen fuel costs are currently higher than traditional fuels, “perhaps by an order of magnitude…” (30). Importantly though, the price of hydrogen is variable according to nation (Raucci, 2014). This fact makes identifying the ports with the lowest cost potential critical to assessing the viability of marine hydrogen (31).

Fuel cell power plants have been limited in their introduction due to their cost (26).

Public policies may benefit the introduction of hydrogen as a marine fuel more than create a barrier. Multiple countries have imposed restrictions on emissions at ports and within a certain distance from shore. These types of policies make hydrogen an ideal solution for oceanic journeys, but also as an auxiliary fuel for propulsion close to shore. Conversely, shipping of liquid hydrogen is currently not allowed by international codes (30). Countries must reach agreements to allow transferring liquid hydrogen between ports before ships using the liquid hydrogen on board. Such an agreement has been reached between Japan and Australia (AMSA, 2017), which will be used to inform other international policy.

2.4.2 Capital Investments Related to Hydrogen

Capital investments include both infrastructure and vessel-related costs. Infrastructure will include electrolysis and steam or biogas reforming facilities, pipelines (transport), storage facilities, and refueling equipment. Recent investments in natural gas infrastructure, hydrogen municipal bus systems, and passenger vehicle refueling stations will be drawn upon to determine storage, transport and refueling costs. Generation investments will similarly be drawn from existing and operating electrolysis and reforming facilities. Vessel-related costs will include fuel cells, cost to retrofit existing ship, and the cost to build new ships designed specifically with hydrogen in mind. Fuel cells are being designed for use in ferries and tugboats, but are not currently available for any size cargo ship. For that reason, assumptions will have to be made for these costs, informed by ferry and tug projects. Retrofitting ships may be loosely based on current retrofitting projects related to natural gas and methanol hybrids, neither of which act as “drop-in” fuels. New ship build will once more be based on existing costs. All three ship-type investments, and all infrastructure costs will require important assumptions, but will be equally important to informing public policy related to hydrogen subsidies. Data will rely heavily on private corporations who may not be willing to share these data, and for that reason assumptions may be required for those companies refusing to contribute. This section will also attempt to capture research and development costs for ship-operators and manufacturers through data collected from those entities.

2.4.3 Economic Analysis of Hydrogen Fuel

As discussed previously, hydrogen fuel is more expensive than all traditional maritime fuels as well as others considered by (30) (LNG, methanol, and biodiesel). This may be a function of scale. Currently hydrogen is only used by a small number of municipalities for transit bus service, a limited number of passenger vehicles (about 11,000 worldwide [Phillips, 2019]), and industry. The scale at which hydrogen will be needed for marine fuel cells may drastically reduce its cost. This section will attempt to project the cost of hydrogen ten years in the future. This is a critical component for ship operators to consider when selecting hydrogen as their fuel of the future.

2.5 Available Fuel Cell Technologies

There are five types of fuel cells that could be used for marine applications: PEMFC, PAFC, MCFC, SOFC, and DMFC (32). Each are suitable for propulsion by (33) suggests ammonia-stored H2 (MCFC and SOFC) are the most likely candidates owning to the lower storage temperature. (30) likewise suggests this, mainly because of the energy leaking effect of storing pressurized hydrogen gas on board. (26) explains one additional fuel cell option, Direct Methanol Fuel Cells (DMFC) has a real opportunity for multiple benefits. Not only can the DMFC operate at high efficiency relative to fossil fuel power plants, but the high heat requirement provides a basis for waste heat recovery used to power other systems (34).

Fuel cell power plants, in their various forms, have been demonstrated to work in maritime applications. (27) describes PEMFC systems in operation in submarines. (34) notes that DMFC may appeal to militaries with submarines and commercial vessels due to the lower operating temperature (50-120ºC for DMFC versus 250ºC for PEMFC). The use of methanol as a reactant is also appealing in submarines since the need for cryogenic and robust metal hydride storage is not needed. The same thought process may apply to surface vessels, although fuel capacity and storage volume is at less premium in commercial vessels. (35) list a number of ferry projects utilizing PEMFC technology, which (36) likewise considers for a sampling of Croatian ferries. The downside to these platforms is the cost of pure hydrogen, a requirement for PEMFC systems.

2.6 Fuel feedstock and infrastructure needs for marine fueling

Maritime fuel cell technologies require three areas of investment to succeed. First is the onboard power system. The industry has not determined which of the previously identified fuel cells are best suited and economically viable for commercial shipping. This will require additional design, testing, and piloting before fuel cells can be adopted widely.

Second is the determination of feedstock. As Table 2-1 outlines below each fuel cell technology has the potential to utilize different reactants. PEMFC is the most restrictive, requiring high purity hydrogen to avoid damage to the anode and cathode (34,37). MCFC is most flexible in terms of reactant consumed. Natural gas, methanol, and even MDO can be processed within the system to produce the gaseous reactants required to produce power. Similarly, solid oxide fuel cells are flexible and reform fuels within the system, but the fuel must be in liquid state(38). Unlike PEM fuel cells, MC and SO fuel cells do emit measurable amounts of CO_2 during operation (39). Finally, DMFC requires methanol to operate, but this fuel is already in use by the industry on dual-fuel ships, so fuel availability is already practical.

The third area of investment is the onshore infrastructure. Natural gas and MDO bunkering, or storage, already exist at nearly every port in the Baltic-North Sea region. The power demands of shipping, however, require renewed investment in this area for fuels like hydrogen and methanol. Methanol can be stored in facilities similar to those for MDO, but hydrogen requires hardened, pressurized storage tanks and certain materials for pipes that can avoid embrittlement.

Table 2-1. Useable fuels in each fuel cell type

Fuel Cell Type	Fuels / Reactants			
	H_2	Natural Gas	Methanol	MDO
PEMFC	✓			
MCFC		✓	✓	✓
SOFC			✓	✓
DMFC			✓	

2.7 Life-cycle and Fuel cycle emissions models

Maritime emissions have been estimated through a variety of models, but which is the most appropriate for comparing alternative fuels? (40) acknowledges that different fuels contribute to global warming at different points in the supply chain, or fuel cycle. Combustible fuels like traditional marine fuels MDO, HFO, and natural gas release the highest amount of GHG during combustion yet the processes of discovering, extracting, transporting, and refining those fuels also release GHGs (41,42). For alternative fuels and reactants that can be used in fuel cells those same upstream activities – extracting, refining or processing, and transportation – can have a bigger climate impact than the use of those fuels onboard a ship (40,43,44).

Marine Life Cycle Analysis Models (LCAs) aim to estimate emissions from shipping not just from the refining or combustion of fuels, but also from construction of the ship, ship operation other than propulsion (lubricants, crew support systems, etc.), and even the disposal of the ship at the end of life (36,45–50). Fuel Cycle Analysis Models (FCA) limit the scope of emissions estimates to Well-to-Wake, considering only those activities that directly contribute to the generation of fuel and use on board a ship (propulsion or otherwise) (45,51). Since marine fuel cell technology is nascent and it is unknown whether the technology can be retrofitted to existing ships or if new power plant designs require new ship builds, it is the author's contention that a fair comparison between fossil fuel propulsion systems and fuel cell propulsion systems can be made using FCA rather than LCA. LCA models can, however reveal valid approaches to the development of a short-sea specific model.

Winebrake et al (2007) (52) developed the GREET/TEAMS model, which does not distinguish between short sailings and ocean-going vessels. TEAMS is a Total Fuel Cycle Analysis (TFCA) tool that considers all upstream emissions from fuel extraction to reaching the vessel. The model is U.S.-specific and utilizing previously developed emissions factors from the GREET program (45,53,54). An important aspect of the TEAMS model is that it identifies common operating states for ships, including power load under those states. The authors had access to fuel consumption data, which limits the applicability to broader studies using publicly available data.

Nian and Yuan (2017) (46) developed an LCA tool specific to maritime operations. This model too focuses on ocean-going vessels in that it designates an optimal speed at which vessels should operate. Again, operating states and power load during those states are identified and can be applied to other vessel trajectories. (46) note that ship operation, or the fuel cycle accounts for the majority of ship lifecycle emissions, reinforcing the notion that it is the proper approach to emissions comparisons. The goal of this work was to develop a replicable model for any ship operation; however, this requires information about fuel consumption that is not readily available.

Bonou et al (55) studied how vessel type and operational profiles can influence emissions. Though presented as an LCA model the assessment is based entirely on Well-to-Wake ("Well-to-Propeller" (55) emissions. The work points out the importance of fuel sourcing on overall emissions, which will play an important role in the development of the Baltic-North Sea emissions model. The energy intensity of HFO derived from Norwegian sources is three times less carbon intensive than those derived from Russian sources (55). Likewise, natural gas feedstocks from Algeria exceed the carbon intensity of Norwegian natural gas. The vessels analyzed in this work are based in the Netherlands, showing the importance of local feedstocks, a notion supported by (40,44,56) when considering hydrogen-based alternatives.

2.8 Vessel energy consumption

The total fuel consumption of a vessel depends on three main factors: power plant design, speed, and total tonnage (deadweight + lightweight) (57). The power plant design determines the amount of power available, the rate at which fuel is consumed (g/kWh), and the overall efficiency of the mechanical operation of the engine (57,58). Speed has been shown to have a cubic relationship with propeller power requirements (57,59). Total tonnage likewise influences the power requirement though to a lesser extent than speed.

The overall performance of a vessel can be influenced by other factors. The age of a ship must be considered. Degradation of the hull over time can lead to protrusions that increase friction between the hull and the water (57). Efficiencies can be lost in the mechanical systems between the powerplant and propeller(s) even with proper maintenance (57). Cavitation at the propeller fins can result in propeller efficiency losses (57). Each of these efficiency losses will influence the input power and amount of fuel consumed to produce that power to achieve the required speed. Chapter 4 will explore how those efficiencies directly impact emissions estimates.

2.9 Gaps in Literature

Fuel cycle emissions models consider marine shipping as homogenous. Feeder, or short sea operations are different than ocean-going vessels utilizing smaller and older ships and even support craft like tugs for barges. This work focuses explicitly on short sea shipping to understand the intricacies of shipping patterns and explore underlying characteristics that can explain emissions from the industry.

Various studies estimate carbon intensity of fuel production based on the country of origin and content or quality of the fuel. Studies do not show emission factor estimates for specific geolocations. This study intends to define those emission factors for individual ports acknowledging that in a country long as Norway, for instance, emissions cannot be the same for Oslo (South), Bergen (Central), or Tromso (North).

Chapter 3: A review of short-sea shipping in the Baltic and North Seas

3.1 Abstract

Short-sea sailings (SSS) are a little studied component of international trade, yet over half the maritime vessels in the world operate within this sphere (60). The ships employed in short-sea operations are often smaller in size and capacity than deep sea vessels (60,61), although as the results in this chapter show these assumptions are only true on average. This chapter describes the current state of short-sea operations in the Baltic and North Seas region according to the literature and provides analysis of ship movements based on AIS data retrieved for June 2023, which will be used in later models. The analysis of AIS data provides clarity on patterns of shipping between countries and specific ports, the type and class of ships in operation, as well as information about ancillary systems in the SSS network – namely support craft such as pilot and tug boats, dredging ship, and offshore platform supply ships.

3.2 Introduction

Baltic Sea shipping is a misnomer in ways. While there are certainly movements of freight between Baltic nations, SSS in the Baltic and North Seas are heavily influenced by Europe's biggest ports, namely Antwerp, Hamburg, and Rotterdam.

One aspect of regional shipping that cannot be overlooked is the presence of offshore oil and gas platforms as well as offshore wind farms. The United Kingdom, Norway, Denmark, Germany, and the Netherlands each possess mineral rights in the North Sea (see Figure 3-1) with additional holdings by Poland and Germany in the Baltic Sea (62,63). Countries operating offshore windfarms in the Baltic or North Sea include Denmark, Germany, Netherlands, Norway, Sweden, and the United Kingdom. These assets generate shipping traffic in the form of tankers carrying crude oil and natural gas, crew transport boats, offshore supply vessels, and heavy lift or towing vessels that transport equipment to and from these locations.

Baltic trade was last analyzed in 2014 (64). Most analyses related toward emissions and considered all Baltic Sea shipping rather than sectors such as shipping, ferries, fishing, or support. The HALCOM estimates are conducted every four years but more often when major policy changes go into effect. For instance, 2024 and 2025 emissions were estimated to compare pre- and post-treatment impacts of low-sulfur content fuel regulations.

For the purpose of this work Short Sea Shipping (SSS) is defined as any vessel active in moving freight or goods in the Baltic and North Seas and coastal waters surrounding those seas. It also includes some inland waterways such as the mouth of the Elbe and canals such as the Kiel Canal (NOK). It does not include inland waterways south of Hamburg, etc. The ships "moving" freight or goods generally do so directly, but it also includes specialized craft for transporting laden trucks (Ro-Ro vessels) and various support craft such as those suppling goods and crew to offshore wind farms and oil fields. Finally, it includes tugboats, pilot boats, and dredging vessels directly required for the continuation of commerce in these waters.

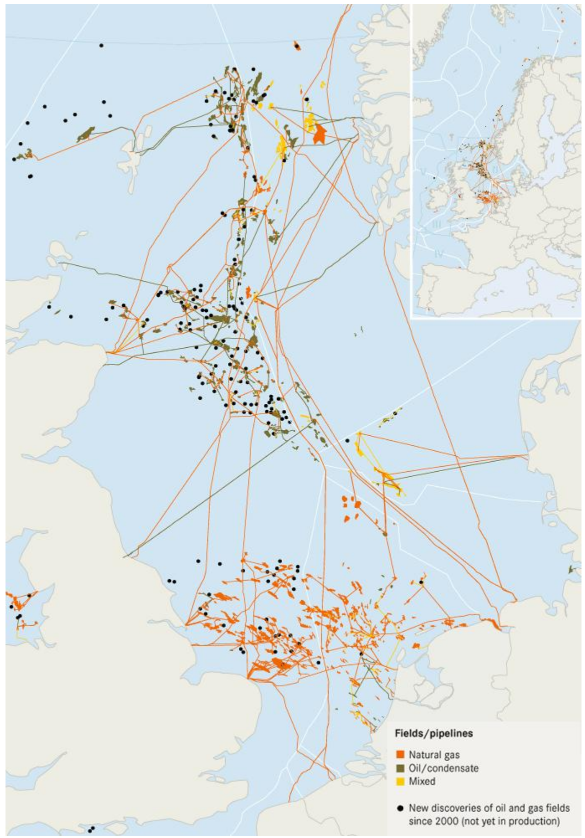


Figure 3-1. North Sea Offshore oil and gas fields (originally published by OSPAR (62)

SSS vessels are not fixed in any area. Rather, they often transport goods between a fixed set of ports regularly for a brief period then move to another area. The period for this study is June 2023. It is likely that many of the cargo and tanker vessels included in this analysis are located in many different places around the globe now. Baltic and North Sea SSS does not mean the vessels are tied exclusively to ports along those seas. Excludes ferry services between France and United Kingdom (mostly Calais-Dover and Dunkirk-Dover routes), but not between Scandinavian and Baltic Countries or the Netherlands and the UK. The later group often has mixed routes, meaning it is not a constant service between two ports, but has a hub-and-spoke system of moving people and freight, visiting multiple ports along the North Sea coast lines in multiple countries.

3.3 Research questions

This chapter serves as a reference point for all subsequent chapters. The data analyzed in this chapter are used for each of the Modified Total Fuel Cycle Models. The categorization of vessel traffic, classification of vessels, and identification of port-related vessel traffic patterns provide context to the emissions estimates as well as the complexity of the short sea shipping emissions problem. These details are determined by answering the following research questions:

1. **What are the SSS activities between Baltic-North Sea region ports?**
2. **What are the types of ship classifications involved in Baltic-North Sea region SSS?**

Specific attention is paid to the Nordic nations of Denmark, Norway, and Sweden from which the data are retrieved and are most complete. In addition to sailing distance and time, the work related to question (1) will provide insights into downtime and loading of these vessels, which is vital to accurate emissions estimates described in later chapters.

The second question relates to the vessels rather than voyages. This pertains both to the types of cargo (e.g., crude oil tanker, bulk freight, and container) and to the relative size of vessels. Cargo carrying capacity, deadweight tonnage, and power plant size are all critical parameters in emissions modeling.

By combining the two previous questions, this work will describe the pattern of goods movement between regions and specific ports based on ship classifications.

3.4 Data

The Baltic and North Seas are bordered by thirteen (13) countries: Belgium, Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Netherlands, Norway, Poland, Russia, Sweden, and the United Kingdom. Each country has ports located along at least one of the two seas and logically import or export freight via short sea shipping from neighboring countries. AIS or Automatic Identification System provides a data format to analyze these freight movements on a range of scales from a single vessel and origin-destination port pairing to network-scale.

AIS data are GPS traces – along with accompanying vessel and directional information – that are transmitted by an onboard transponder to either a landside or satellite receiver. This live vessel tracking is used by vessel traffic services (VTS), coast guards, and other ships to avoid collisions and provide safety updates in aberrant weather or during nearshore and offshore operations such as dredging. AIS transponders are required on any vessel traveling internationally that measures 300 tons or more (gross tonnage) as well as a few other stipulations (65).

The AIS data for this research comes from archives hosted by two countries: Denmark and Norway. The historic AIS data come from:

- Danish Maritime Authority historic AIS data (2023) (66)
- Norwegian historic AIS data (2023) (67)

AIS data is collected from most ships on average every 10 seconds (68). In practice, there are multiple receiver stations within range of AIS transponder signals and often the information is recorded multiple times in archived datasets. For the two countries included in the study, the coverage areas overlap and single events were often recorded by each country.

There are 26 standard pieces of information relayed in AIS transmissions. These are divided into static and dynamic information. Static information includes ship details such as IMO registration number, flagged country, and ship name. Dynamic information includes status updates: current speed, heading, and draft (or draught). A complete list of information transmitted in AIS signals is shown in Table 3-1.

Table 3-1. Information transmitted in AIS signals

Static Information	Dynamic Information
• Type of transponder (A for vessels > 15m, B for all others) • MMSI: unique AIS identifier for ship • IMO (IMO registration number) • Callsign • Name (vessel name) • Ship type (cargo, tanker, sailing, etc.) • Cargo type • Width • Length • Type of position fixing device • Data source type • Sizes A-D (distance from GPS to bow, stern, starboard, and port, respectively)	• Timestamp (transmission date/time • Latitude • Longitude • Navigational status (e.g., moored, under way, etc.) • Rate of turn • Speed over ground • Course over ground • Heading • Draught • Destination • ETA

3.4.1 Geographic Coverage

In concept, AIS tracking is performed by any country with sea access, and the area of that country's responsibility overlaps with its Exclusive Economic Zone (EEZ). The EEZs of Denmark, Norway, and Sweden border one another, guaranteeing AIS coverage within 200km of any of these countries. The EEZs are shown in Figure 3-2(a).

AIS coverage often extends beyond the area of the EEZ. Norway serves as the E.U. clearinghouse for the North Sea, Barents Sea, Northern Atlantic, and Baltic Sea AIS transmissions. This is due to its position relative to those seas, possession of remote territories like Svalbard that lie outside coastal EEZ boundaries, and the country's significant maritime presence in the North Sea due to offshore oil drilling. On average 5,000 vessels can be tracked within Norwegian waters on any given day, but the AIS repository collects tracking information from over 12,000 vessels within this larger geographic area. As such, Norway's repository overlaps with Denmark's significantly, especially North and West of Denmark's Jutland peninsula. Denmark's coverage extends East to the island of Bornholm, providing coverage across Germany's Northeast and Poland's coast. Sweden's tracking sufficiently overlaps with Finnish, Russian, Estonian, Latvian, and Lithuanian waters in the Baltic sufficiently to cover the entire sea between these three countries. The measured extent of the Nordic countries' AIS coverage is shown in Figure 3-2(b).

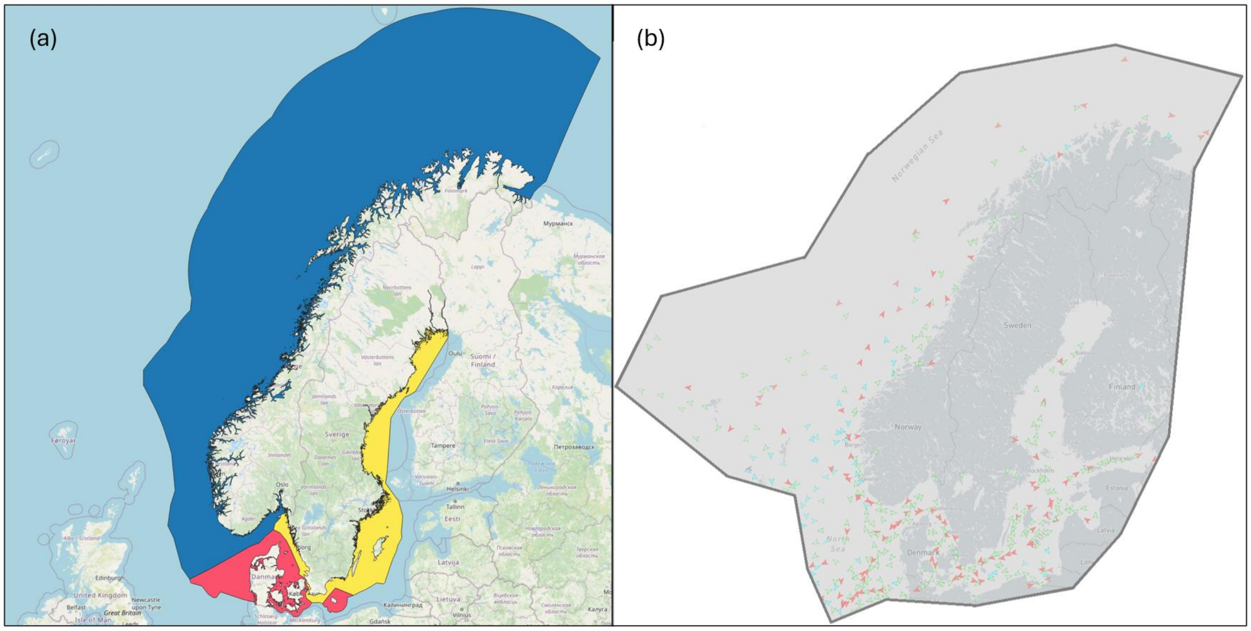


Figure 3-2. (a) Exclusive Economic Zones of Denmark (red), Norway (blue), and Sweden (yellow). (b) Actual extent of AIS data coverage for study period (June 1-30, 2023).

3.5 Data Processing

In later chapters an emissions model will be demonstrated across all SSS vessels in a one-month period (June 2023). The results in this chapter similarly reflect this period, however data were collected for three (3) months: May, June, and July. The reason for this is two-fold. First, analyzing the travel patterns of ships before and after June allows for confident classification between ocean-going craft and short sea vessels. Often, ships appear in the June data for just three to four days at the beginning or end of the month or are moored for an extended period during June. Reviewing AIS traces before and after those periods informs us as to whether the ship arrived from or departed for ports outside Europe. Second is to address ship behavior in the three ports of Antwerp, Hamburg, and Rotterdam. It is commonplace for both ocean-going and short-sea vessels to visit more than one of these ports in the same voyage. It is also common for ships to visit these three ports exclusively. In the latter case we can consider that vessel as a short-sea vessel. Its voyage distance is short, and it never leaves the continental shelf. Reviewing June data alone leads to a false positive classification rate for ships visiting more than one of these three ports of 31%.

It was assumed that a ship's pattern of movement within that 30-day period would indicate whether it could be classified as a SSS vessel. Deep sea ships tend to remain at berth for 1-2 days, are given priority access to berthing over smaller and lightly laden vessels, and would leave the area for at least 14 days. SSS vessels, conversely, remain at berth for both shorter (due to less cargo) and longer periods (due to demand), may remain anchored or stationary outside major ports for extended periods while waiting for ocean-going vessels to depart, and if the vessel departs the area, it returns relatively quickly.

3.5.1 Data Cleaning

The AIS data requires cleaning to minimize computational cost. An average data file from each country will contain 15-19 million AIS entries from 9,067 unique vessels (median value). It should be noted that vessel traffic in June is not representative of a full year. First, June is within what is referred to as the "doldrums" for freight. Traffic is lighter until year-end holiday trade increases and Northern hemisphere harvests are shipped. This is especially true for containerized freight that bears mostly consumer goods and components of goods. This analysis benefits from fewer container ships to purge from SSS files. But the same pattern is not necessarily true for bulk freight. In fact, for certain important industries to the region such as lumber, summer represents the best time for harvesting and therefore shipping. Personal craft activity is heightened due to warm weather and summer holidays. This is best demonstrated by the aggregate number of unique sailboats (7,283) observed versus unique cargo vessels (3,090).

Each daily file was cleaned before being merged with files for each country. While live AIS is viewed as reliable, the historic data does contain errors. Notably these include determining the ship's location as above 90 degrees latitude when the transponder goes out of range. This does not occur for every vessel, but the error is present frequently enough to become problematic when calculating speed and destination or origin later in this analysis. A second issue to the formatting of date-time series. Most dates are formatted in the standard DD/MM/YYY format, but many datapoint randomly switch to MM/DD/YYY format within a single ship's observed path. These dates needed to be reformatted before proceeding.

A third issue is related to the destination column. Owing to human interaction with the system, multiple manufacturers producing and coding transponders, and a lack of IMO standardization, the destination information is inconsistent between vessels. One vessel traveling toward Gothenburg, Sweden may record that as "SEGOT" – the UNLOCOE for this port. Another ship may use "Göteborg SE," and a third may indicate origin and destination for the same trip: "NLRTM>>SEGOT." The destinations must be standardized during the cleaning process to gain proper perspective on travel patterns. This process occurs after prospective SSS vessels have been identified rather than with the full dataset.

Origin and destination information is missing from the data in 4 scenarios. These ports were identified specific to the condition. First, dynamic information from AIS traces (location, headings, etc.) are recorded at various times without recording the origin, destination, draft, and some static information including ship dimensions. These records most often occur during a voyage or while the vessel is station keeping. Missing information was filled in using entries that most closely reflect the ship's heading, timestamp, and location. Second, when a vessel approaches a berth or departs a port for a new destination series of AIS traces do not record this information. In these cases heading and draft are used to determine the missing information.

The third and fourth scenarios of missing information are related to the port of origin, which is not recorded in AIS systems. In voyages with destinations in a series the predecessor destination is always used as the origin of the successor destination. These are easily identifiable except for the first destination. If a ship is identified as one that repeats a voyage, the successor destination is used. For ships with unique series of destinations, inspection was expanded to include May

2023 AIS traces. The final destination in the May record that differs from the first destination of the June record is used as the origin. AIS traces were also reduced from 10-second intervals to 30-minute intervals. This is adequate time to determine speed and course changes.

3.5.2 Identifying SSS Vessels

There are two elements that are highlighted by AIS directly that can determine a short sea vessel from a deep-sea ship. Those are: ship type and destination. The cleaned data are first narrowed by ship type. Figure 3-3 shows the decision tree for determining if a ship could be considered for SSS classification based on ship type. There are two ship types that can be automatically considered for inclusion: “Cargo” and “Tanker.” Cargo covers bulk carriers, general cargo, container, some roll-on-roll-off, reefer, heavy lift and inland general cargo vessels. Tanker covers LNG, LPG, bunkering, floating storage, crude oil, general chemical or oil, and inland tankers. Importantly, each category includes inland vessels, which need to be scrubbed from the sample later.

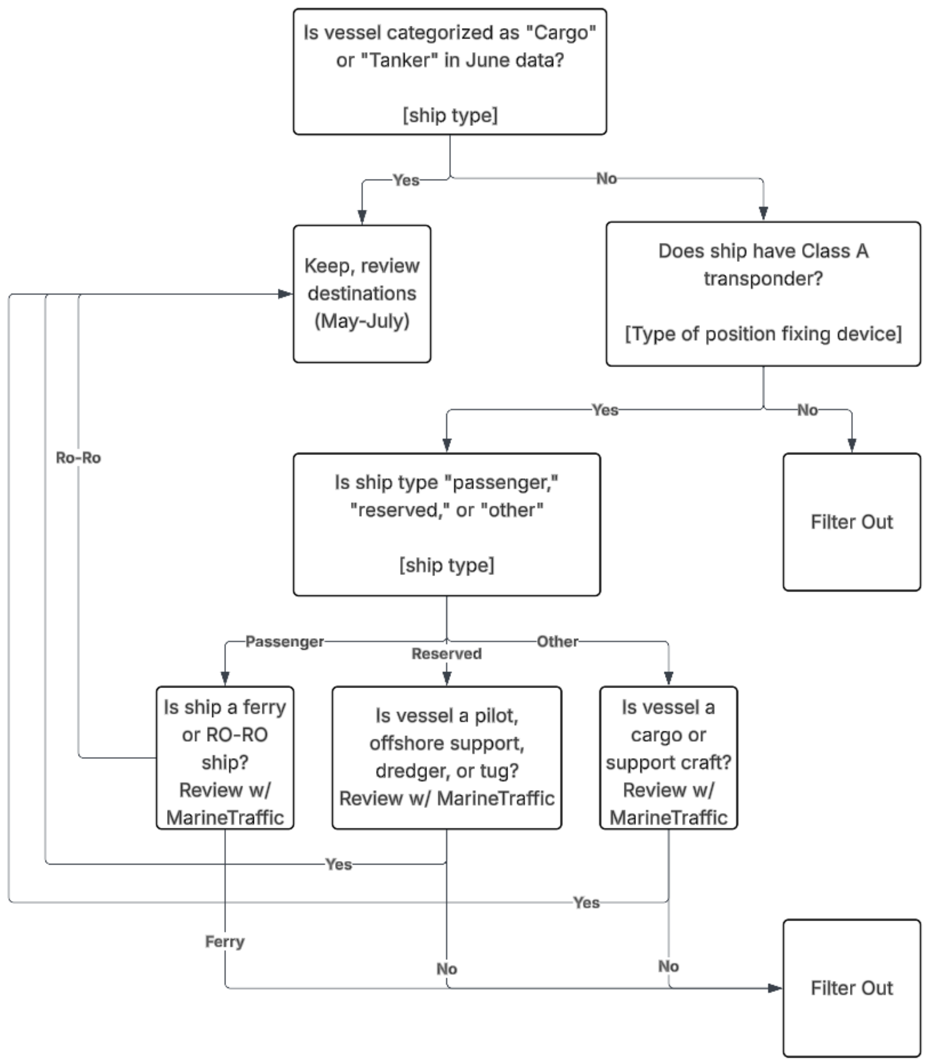


Figure 3-3. Decision tree for identifying potential SSS vessels

The first step is to eliminate Class B AIS transponders. These are almost universally used for personal craft, and vessels less than 15 meters in length (sailboats would be included here). Class B transponders tend to be less expensive, but there are no regulations barring a ship owner from using a Class A transponder on any vessel type. The next filter applied is for “ship type.” Six types fit the definition of a SSS craft: “Cargo,” “Tanker”, “Pilot”, “Port Tender”, “Towing”, and “Tug”. Cargo includes any type of dry or containerized freight, so the vessel types include container ships, RO-RO (Roll-On, Roll-Off) vessels, bulk carriers, reefer vessels, and general cargo ships. Pilot, port tender, towing, and tugboats were re-classified as support craft. Table 3-2 shows the number of each ship type observed in the AIS data.

The ship type “passenger” includes both SSS-involved vessels (RO-RO ships) and those primarily used for moving passengers. In many cases they are ferries, which do sometimes carry delivery vehicles, but that is not their primary purpose, so they are omitted from the analysis. The category also includes cruise ships, water taxis, tour boats, and some private tenders. All of these were removed from consideration as SSS vessels as well.

Other categories of ships within “Ship type” were explored to determine if any SSS vessels had overlap with these categories. “Reserved” vessels mainly consist of port infrastructure, marine structures, equipment that can be used in water such as crane barges for dredging, and research or surveying vessels. None of these are directly involved in SSS. “HSC” vessels, short for high-speed craft, include crew transport boats and high-speed passenger ferries, but no vessels that are responsible for transporting goods or freight. It should be noted that in a cursory review of “undefined” vessels, there are possible SSS vessels present, but the sheer number of vessels within that data is overwhelming. All succeeding analysis of SSS vessels is therefore a sample rather than population.

A total of 6,492 vessels were selected for determination as SSS vessels. Table 3-2 shows the total vessels that were included in the SSS vessel screening process that will be discussed next. Unique vessels were identified by their Maritime Mobile Service Identities (MMSI) numbers. These are unique to each ship with an AIS transponder.

Table 3-2. Vessels included in classification and screening

SHIP TYPE	**NO. OF UNIQUE MMSI**
CARGO	3,090
TANKER	1,318
DREDGER	266
PASSENGER	924
PILOT	147
PORT TENDER	120
TOWING	82
TUG	530
TOTAL	**6,492**

The next step of data processing requires additional information to be collected for each vessel. MarineTraffic and MyShipTracking (69,70) were scraped for MMSI records to determine the specific type of vessel included in the categories shown in Table 3-2. Pilot, port tender, tugs, and dredgers were reclassified here as "Support" vessels. During this screening phase two additional activities were defined: Out-of-Service (OOS) and Lack of Data (LOD). OOS means a ship is located in a port that is associated with SSS but is moored for the entire period it is observed. Often these observation are 3-4 days or 1-2 weeks indicating ship power is active by the ship may be under maintenance or is awaiting a load. LOD was assigned if the vessel had too few data points to determine if it remained in the Baltic-North Sea area or lacked identifiable information (MMSI was missing from a small number of records) (69,70). Most often the ship is located within a port or in nearby waters, but movement is not observed, destination is not defined, or direction of travel cannot be determined. These vessels are subsequently excluded from the analysis.

3.5.3 Classifying SSS, Deep-Sea, Inland, and Support Vessels

To determine if a vessel is involved in SSS, each voyage must be inspected. There are a few parameters that can be used in order of strictness: 1) destination is in Europe, and 2) whether the ship has made port in the Baltic Sea. There are ships that are involved in SSS but not exclusive to the Baltic Sea. To better understand the market for Baltic SSS vs. European SSS at large, each ship is assigned a category that reflects the path of travel and/or the ports that are visited. SSS vessels can be assigned 1, 2, or 3 of these categories.

- **Baltic**: Denmark, eastern German ports, Estonia, Finland, Latvia, Lithuania, Poland, Russia, or Sweden
- **Northern Europe** (centered around North Sea access): Belgium, Denmark, Faroe Islands, Netherlands, northern Russian ports, Norway, United Kingdom, western German ports
- **Other Europe**: France, Ireland, Spain, Portugal, Mediterranean ports, and Black Sea ports

Destination is typically, but not consistently, identified by UNLOCODE in the AIS dataset. This naming convention lists the port's unique five-letter code with the first two indicating country (e.g., DE for Germany, NO for Norway, and PL for Poland) and the last three indicating the specific port. Any nautical access point can be assigned a UNLOCODE, including those that do not service freight vessels, a point that will be returned to later.

There are a few notable exceptions to the short sea designation. Any ports of call in Egypt are assumed to continue their voyages through the Suez Canal. Iceland and Greenland are excluded though the former is a European nation, and the latter is included in the Danish realm. Both require deep sea voyages.

The defining feature of deep sea versus short sea in the sample set is ports of call. A one-month travel history (June 2023) of each ship was used for emissions calculations and the results reported in this chapter, but vessels often spend a month or more in a region even if not directly involved in SSS due to scheduled routes controlled by the carriers. For that reason, a three-month timespan was used to determine ocean-going or otherwise. If a destination appears in a ship's three-month voyage history that was outside of the regions described above, the ship is classified as deep-sea.

SSS versus deep sea generally applies only to cargo ships and tankers. But these same ship types, as well as tugs and pilot boats, can be involved exclusively in inland waterway activity. Germany and the Netherlands especially, but to a lesser extent Poland, Norway, and Sweden have vessels appearing in their territory that are not rated for sea travel and indeed never leave inland navigable waterways. A separate classification was created for these vessels.

Finally, the remaining support craft were given a SSS designation if they consistently traveled into the Baltic or North Sea or moved within a port frequented by SSS vessels. Table 3-3 shows the final designations of the sample. Table 3-4 shows a complete list of ship class and all activity classifications.

Once SSS ships were identified, the ports of call were reviewed. Any that fell outside the SSS categories (Baltic, North Sea, Europe-other) were flagged and the vessels removed. Second, the ports of call were reviewed. Ships do not always report a port as their destination. This is problematic for vessels that are mid-voyage at the end of the study period. The ports were all individually reviewed to confirm they can accommodate cargo or tanker vessels and have a recent history of doing so. The list of ports was also reduced by ports that were only visited by support craft rather than SSS vessels *and* their support craft.

Table 3-3. Vessel classifications after voyage analysis

SHIP TYPE	NO. UNIQUE OBSERVATIONS	NO. CLASSIFIED AS SSS
CARGO	3,090	1,785
TANKER	1,318	798
SUPPORT CRAFT (PILOT, TUGS, ETC.) + OTHER	1,160	535
PASSENGER	924	43
TOTAL	**6,492**	**3,161**

It is worth noting the inclusion of passenger vessels as SSS vessels. These are exclusively Ro/Ro vessels that operate between countries such as France and the United Kingdom or Sweden and Poland (two common pairings). While these ships may offer passenger service it is typical for most of the capacity to be utilized for truck-and-trailer freight movement, with passenger cabins reserved for use by the truck drivers.

Table 3-4. Vessel class and activity classification

Vessel Type	SSS	Deep_Sea	Inland	Support	Passenger	Out of Service, LOD or Fishing	Total
Cargo							
Bulk Carrier	243	291	0	0	0	40	574
Container	340	124	0	0	0	16	480
General Cargo	944	277	0	32	2	51	1,306
Heavy Lift	35	11	0	0	0	17	63
Reefer	28	17	0	0	0	1	46
Ro_Ro	194	49	0	1	0	6	250
Inland General Cargo	0	0	349	0	0	22	371
Cargo Total	**1,785**	**769**	**349**	**33**	**2**	**153**	**3,090**
Tanker							
Bunkering Tanker	23	0	0	0	0	1	24
Chem/Oil_Tanker	525	193	2	2	0	23	745
Crude_Oil_Tanker	130	137	0	0	0	0	267
Floating_Storage	0	0	0	14	0	0	14
LNG_Tanker	37	19	0	0	0	4	60
LPG_Tanker	83	29	0	0	0	2	114
Inland_Tanker	0	0	94	0	0	0	94
Tanker Total	**798**	**378**	**96**	**16**	**0**	**30**	**1,318**
Support							
Crew Transport	6	0	0	0	0	0	6
Dredger	24	0	0	157	0	0	181
Nearshore support	6	0	1	252	0	0	258
Offshore_Platform	1	0	0	1	0	0	2
Offshore_Support	108	0	0	1	0	0	109
Offshore_Supply	33	0	0	3	0	1	36
Pilot	136	0	1	0	0	1	138
Tug/Towing	221	0	146	34	0	0	401
Support Total	**535**	**0**	**148**	**448**	**0**	**2**	**1,131**
Passenger							
Cruise	0	0	0	0	106	0	106
Ferry	0	0	0	0	531	0	531
Pax_&_Ro_Ro	43	0	0	0	1	0	44
Private	0	0	0	4	239	0	243
Passenger Total	**43**	**0**	**0**	**4**	**877**	**0**	**924**
Other							
unknown	0	0	0	0	0	8	8
Fishing	0	0	0	0	0	21	21
Other Total	**0**	**0**	**0**	**0**	**0**	**29**	**29**
Grand Total	**3,161**	**1,147**	**591**	**500**	**879**	**214**	**6,492**

3.6 Results

SSS is defined as the transportation of goods over short distances over open water. Most SSS research presupposes assumptions: 1) SSS vessels are older than deep sea counterparts, 2) SSS vessels are smaller than deep sea vessels, and 3) SSS vessels transport freight on shorter voyages that are routine and repetitive. This section will review the Baltic-North Sea dataset to determine if those assumptions are accurate. Additionally, it will explore the patterns of trade within and without the region and determine the types of services offered by carriers according to patterns revealed by AIS traces.

3.6.1 Assumption 1: Short sea ships are older than deep sea vessels

The premise for this assumption is that when a deep sea vessel nears its end of design life it is sold or transferred to carriers focusing on SSS operations. In this way maintenance and the associated cost is reduced. This also assumes ships are not built to order for SSS, only for deep sea shipping, which may run counter to the next assumption that SSS vessels are smaller than deep sea vessels. That being said, ships have increased in size (length and DWT) over time so older ships do tend to be smaller than more modern vessels.

The Baltic-North Sea data show that SSS vessels are older than deep sea vessels, but to a limited extent. Table 3-5 shows the age range of each vessel type, sector type, and overall age range for short sea and deep sea vessels. Figure 3-4 shows the distribution of ship age for both shipping designations. Since data were historic the age represents the age at during the year of archiving (2023). It was not determined how many of these ships are still in service.

Table 3-5. Age range of SSS and Deep Sea Vessels (Years)

	Short Sea Vessels						Deep Sea Vessels						
Ship Type / Sector	Count	Low Age	First Quartile	Median (Medsss)	Third Quartile	High Age	Count	Low Age	First Quartile	Median (Medsss)	Third Quartile	High Age	Diff (Med_{SSS}-Med_{DS})
Cargo													
Bulk	243	0.0	7.0	12.0	15.0	56.0	291	0.0	8.0	12.0	14.0	45.0	0.0
Container	340	0.0	10.0	15.0	18.0	36.0	124	1.0	9.0	15.0	17.8	35.0	0.0
General Cargo	944	0.0	12.0	18.0	26.0	122.0	277	0.0	12.0	16.0	23.0	48.0	2.0
Heavy Lift	35	1.0	6.0	10.0	15.0	31.0	11	4.0	12.0	15.0	23.0	41.0	-5.0
Reefer	28	14.0	23.3	25.5	34.0	45.0	17	2.0	13.0	25.0	31.5	37.0	0.5
Ro_Ro	237	0.0	8.0	15.5	23.0	43.0	49	0.0	10.0	15.0	18.5	45.0	0.5
Cargo Total	**1,828**	**0.0**	**11.0**	**16.0**	**23.0**	**122.0**	**769**	**0.0**	**10.0**	**13.0**	**18.0**	**48.0**	**3.0**
Tanker													
Bunkering	23	1.0	7.5	17.5	29.0	68.0	0	n/a	n/a	n/a	n/a	n/a	n/a
Chem/Oil	526	0.0	9.0	14.0	17.0	52.0	193	0.0	7.0	14.0	17.0	41.0	0.0
Crude Oil	130	0.0	4.0	7.0	14.0	21.0	137	1.0	10.0	14.0	18.0	26.0	-7.0
LNG	37	0.0	4.0	5.0	12.0	17.0	19	1.0	2.0	5.0	10.0	19.0	0.0
LPG	83	0.0	8.0	12.0	16.0	25.0	29	0.0	6.0	8.0	12.5	21.0	4.0
Tanker Total	**799**	**0.0**	**7.0**	**13.0**	**17.0**	**68.0**	**378**	**0.0**	**7.0**	**14.0**	**17.0**	**41.0**	**-1.0**
Overall	**2,627**	**0.0**	**10.0**	**15.0**	**21.0**	**122.0**	**1,147**	**0.0**	**9.0**	**13.0**	**18.0**	**46.0**	**2.0**

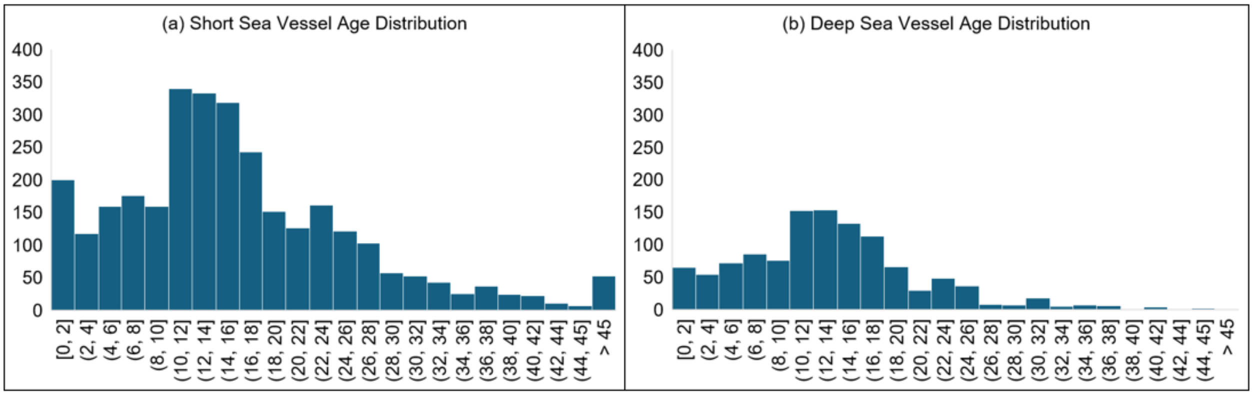


Figure 3-4. Distribution of (a) Short Sea and (b) Deep Sea vessel ages

The difference in age depends on the vessel type. SSS tankers are actually more recently built or the same median age as deep sea tankers. The exception to this pattern is LPG tankers, which are four years older based on median values. The overall age difference was driven by the outsized impact of general cargo vessels on the rest of the sample. Almost 1/3 of SSS vessels are categorized as general cargo and the median age of these ships two years greater than deep sea general cargo ships. Ro-Ro and reefer ships are also older than ocean going vessels of the same type based on the median ages, by 0.5 years.

Heavy vessels operating in SSS services are 5 years newer than deep sea heavy lift vessels, but this sample is limited in observations. It was noted during inspection of May-July that these vessels do remain in the region for an extended period of time and alternate between deep sea and short sea operations. SSS crude oil tankers are also more recently built, however the same operational patterns exist as heavy lift vessels. Crude oil tanker might shuttle oil between offshore rigs and a local port for a month but then might be dispatched to a SSS port in the Mediterranean (Turkey was the most common destination), return, and be dispatched to Africa or South America.

The table above excludes support craft from the comparison. These vessels have an older distribution of build year. They also service or enable both SSS *and* deep-sea shipping as they largely visit the same ports of call and cannot be used to compare the two sectors. Support craft age ranges are shown in Table 3-6. The distribution of ages for most support craft types are similar to SSS and deep sea vessel.

The historic AIS dataset included more than 400 inland freight vessel trajectories. However, ship design information and build year were not easily accessible for these types of ships. Most do not register with global AIS services because they do not travel outside the EU. It is noted that the median ages of vessels with information available are 50.5 and 17 for inland cargo and inland tanker, respectively.

Table 3-6. Age range of Baltic-North Sea support craft (years)

Vessel Type	Count	Low age	First quartile	Median	Third quartile	High age
Crew Transport	6	1.0	1.0	9.5	32.8	35.0
Dredging	24	3.0	8.8	12.5	25.0	56.0
Nearshore Support	6	6.0	11.0	24.0	44.5	54.0
Offshore Platform	1	n/a	n/a	12.0	n/a	n/a
Offshore Supply	33	2.0	8.0	10.5	19.0	57.0
Offshore Support	108	0.0	11.0	13.0	20.0	68.0
Pilot	136	0.0	5.0	11.0	23.0	48.0
Tug/Towing	221	0.0	11.0	19.0	35.0	69.0
Support Total	**535**	**0.0**	**9.0**	**14.0**	**26.0**	**69.0**

3.6.2 Assumption 2: Short sea ships are smaller than deep sea vessels

There are two metrics by which ship size can be readily compared: length (LOA) and deadweight tonnage (DWT). Modern ships are often designed to fit within a classification system based on maximum operating characteristics of certain waterways. Those dimensions are LOA, beam or width, and draft, all limited by the size of locks or shipping lanes. Panamax (294m/32.3m/12m), Post-Panamax (366m/51.25m/15.2m), and Suezmax (400m/77.5m/20.1m) are frequently used as these design parameters. DWT directly determines a ship's maximum draft. Ocean-going vessels can exceed these dimensions but due to the rotation of ships to other services or liner schedules, they rarely do.

A restriction to Baltic-North Sea shipping is the Kiel Canal in Northern Germany. Ships are limited to dimensions of 180m in length, 32.5m beam width, and 9.5m draft. Vessels exceeding this size, however, can travel around Denmark to enter either sea. The vessels, then, are only limited by the allowable dimensions of the ports, many of which are "deep sea" ports.

Dedicated deep sea vessels are larger than short sea vessels, but like ship age this depends on the vessel type. Table 3-7 describes the ranges of size for each vessel type. Figure 3-5 shows cumulative distribution function (CDF) plots for all tankers, all cargo vessels, and a select number of vessel types. Bulk freighters, Ro-Ro vessels, crude oil tankers, and LNG tankers all fall within roughly the same size ranges from first quartile to third quartile. Only SSS crude oil tankers are larger (based on a comparison of the medians) than deep sea counterparts, but even in this case the central distribution range of lengths is nearly identical.

Table 3-8 Compares the sizes of SSS vessels and deep-sea ships based on DWT. Figure 3-6 shows similar information in CDF plots for the same series of vessel classifications as the previous metric. DWT tonnage is a measure of carrying capacity. It does not indicate the utilization of that capacity, which will be explored later in this chapter. Similarly to the length metric, deep sea vessels exceed SSS in DWT for nearly every ship type. The exceptions are general cargo, which are universally smaller than canal-based classification dimensions. This is likely the nature of general cargo ship capacity demand. Though flexible in their ability to carry a variety of cargo types, general cargo ships cannot maximize efficiency through near constant demand as bulk freights, container vessels, and crude oil tankers can. Again, crude oil tankers are the only ship type in which SSS size exceeds deep sea vessels.

Table 3-7. Comparison of ship size (LOA) ranges between SSS and Deep Sea vessels

	Short Sea Vessels						Deep Sea Vessels						
Ship Type / Sector	Count	Low	First Quartile	Median (Medsss)	Third Quartile	High	Count	Low	First Quartile	Median (Medsss)	Third Quartile	High	Diff (MedSss-MedDS)
Cargo													
Bulk	243	55	176	190	225	295	291	90	180	190	228	300	0
Container	340	80	144	198	305	400	124	15	210	293	334	400	-96
General Cargo	944	11	88	90	114	299	277	14	89	107	145	400	-17
Heavy Lift	35	89	144	150	180	275	11	150	160	169	173	217	-19
Reefer	28	63	83	140	156	185	17	131	150	157	164	190	-17
Ro_Ro	237	58	162	195	208	265	49	107	182	199	203	296	-5
Cargo Total	**1,828**	**11**	**90**	**132**	**189**	**400**	**769**	**14**	**133**	**180**	**225**	**400**	**-48**
Tanker													
Bunkering	23	14	43	80	100	166	0	n/a	n/a	n/a	n/a	n/a	n/a
Chem/Oil	526	25	105	135	180	400	193	10	152	183	184	499	-49
Crude Oil	130	144	244	250	274	336	137	90	244	249	273	340	1
LNG	37	108	171	290	299	315	19	155	290	295	299	315	-5
LPG	83	84	98	108	159	225	29	95	138	160	180	225	-52
Tanker Total	**799**	**14**	**107**	**145**	**184**	**400**	**378**	**10**	**180**	**185**	**249**	**499**	**-40**
Overall	**2,627**	**11**	**93**	**136**	**186**	**400**	**1,147**	**10**	**149**	**183**	**229**	**499**	**-49**

Table 3-8. Comparison of ship size (DWT kilotons) ranges between SSS and Deep Sea vessels

	Short Sea Vessels						Deep Sea Vessels						
Ship Type / Sector	Count	Low	First Quartile	Median (Medsss)	Third Quartile	High	Count	Low	First Quartile	Median (Medsss)	Third Quartile	High	Diff (MedSss-MedDS)
Cargo													
Bulk	243	0.8	31.9	40.4	74.3	182.9	291	0.2	35.8	55.8	79.6	207.6	-15.5
Container	340	1.9	11.8	34.5	103.9	242.0	124	7.3	38.0	67.0	113.3	254.0	-32.5
General Cargo	944	0.3	3.5	4.4	6.7	96.6	277	1.6	3.7	5.7	14.4	229.0	-1.3
Heavy Lift	35	5.0	13.0	17.1	31.7	116.2	11	9.1	10.7	17.2	21.4	54.0	-0.1
Reefer	28	0.7	2.7	8.0	12.9	17.1	17	7.7	10.5	12.9	15.4	23.2	-4.9
Ro_Ro	237	0.3	7.3	12.5	18.4	47.5	49	4.5	13.5	19.9	22.7	55.8	-7.5
Cargo Total	**1,828**	**0.3**	**4.2**	**8.0**	**23.5**	**242.0**	**769**	**0.2**	**9.3**	**33.8**	**61.4**	**254.0**	**-25.8**
Tanker													
Bunkering	23	0.2	0.7	3.5	4.2	12.4	0	n/a	n/a	n/a	n/a	n/a	n/a
Chem/Oil	526	0.3	6.0	13.2	35.3	192.2	193	1.8	20.0	45.9	50.1	158.8	-32.8
Crude Oil	130	17.0	106.5	113.6	153.8	318.7	137	2.4	106.0	113.0	141.8	320.2	0.6
LNG	37	3.1	14.7	88.7	95.4	122.1	19	12.3	88.8	93.1	95.4	107.0	-4.4
LPG	83	1.8	4.0	6.0	18.2	54.4	29	3.7	12.7	18.5	26.0	54.6	-12.6
Tanker Total	**799**	**0.2**	**6.1**	**16.7**	**50.0**	**318.7**	**378**	**1.8**	**37.3**	**50.7**	**110.0**	**320.2**	**-34.1**
Overall	**2,627**	**12.0**	**4.5**	**9.7**	**33.4**	**318.7**	**1,147**	**0.2**	**14.1**	**39.4**	**80.4**	**320.2**	**-29.7**

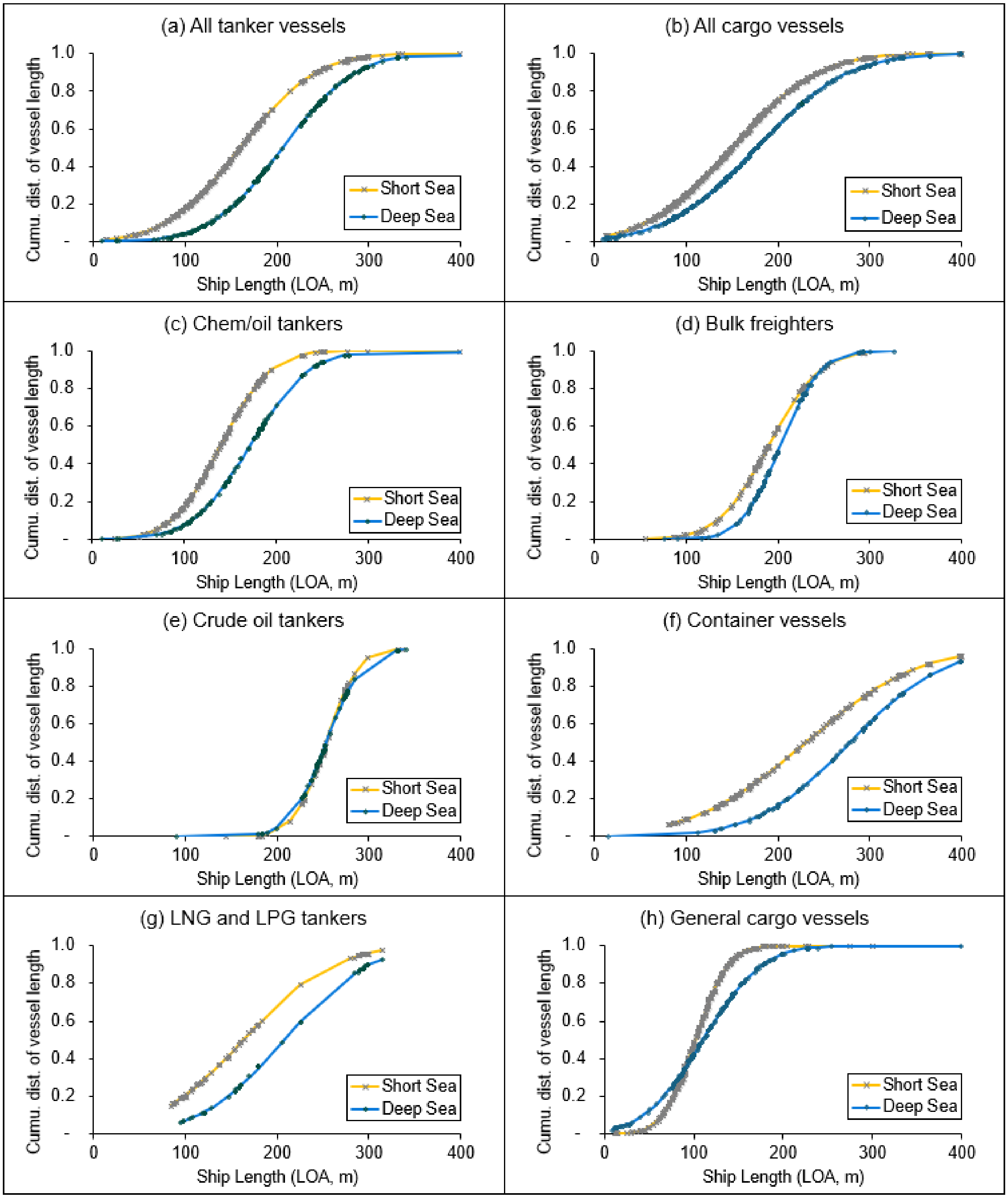


Figure 3-5. Cumulative distribution of ship sizes by LOA (m)

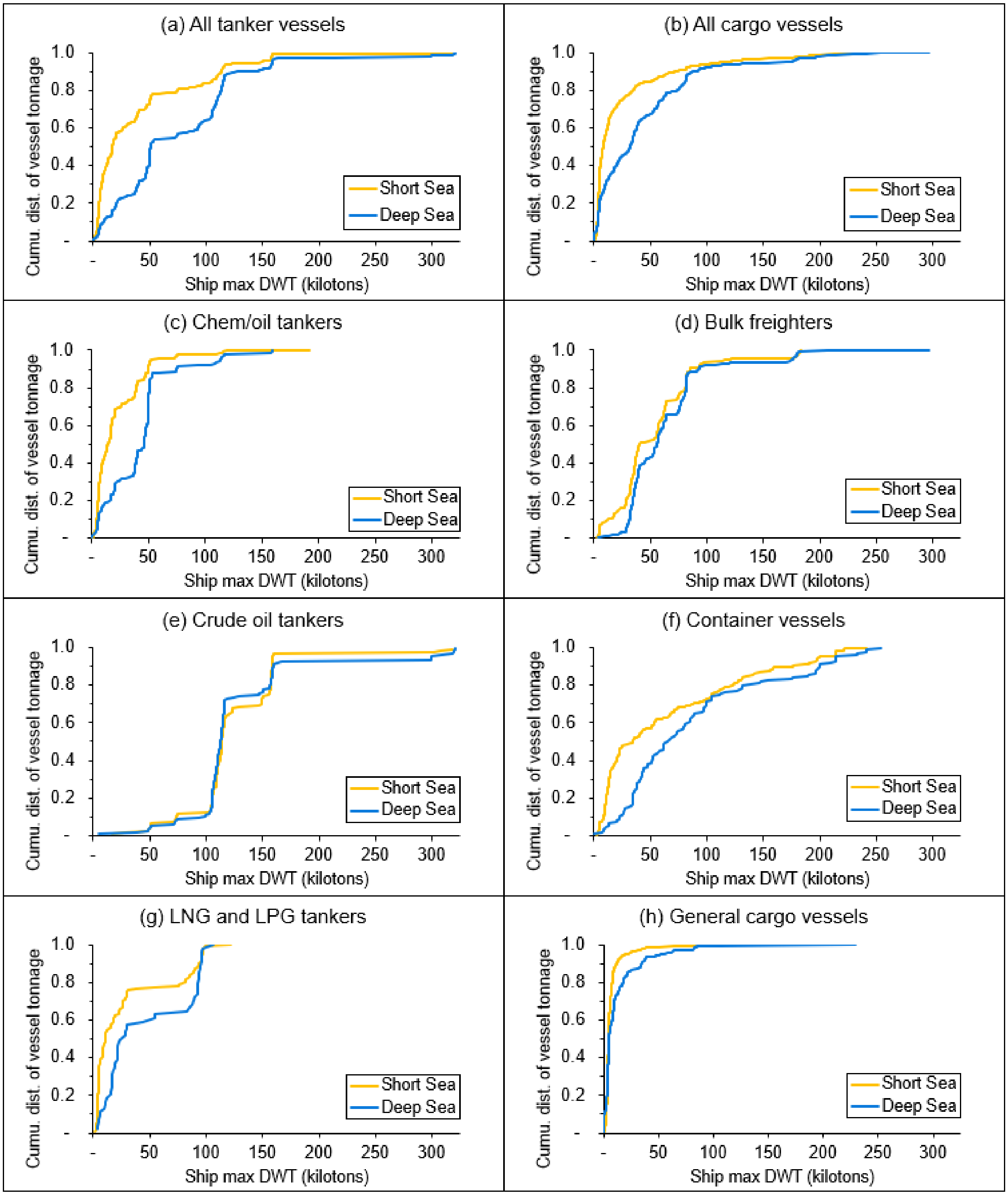


Figure 3-6. Cumulative distribution of ship sizes by DWT

Crude oil vessels are the largest vessels on average, although some main-line container ships are used to shuttle containers between ports like Antwerp (BE), Rotterdam (NL), Hamburg (DE), Gothenburg (SE), and Felixstowe (UK) and have been categorized as SSS. It should be noted that some SSS vessels participate in both SSS and deep-sea activities. They may spend a season in a single region then return to scheduled service between European ports and ports abroad during busier periods. Crude oil vessels may be an exception here due to the near-constant demand from offshore rigs to shore.

3.6.3 Assumption 3: SSS vessels transport freight on shorter voyages that are routine and repetitive

Comparisons between deep sea and SSS vessel voyage length cannot be made due to the lack of full trajectory information, but we can determine the distance between ports of call is by and large shorter if the deep-sea vessels leave European waters. Table 3-9 provides an overview of total voyage length (in nautical miles) by vessel type within the observable geographic coverage of the AIS data. This table also details the number of ports of call per voyage and the average distance between ports of call. It does not measure distance traveled for ports of call outside of the Baltic-North Sea Region. Figure 3-7 further explores the distribution of total voyage lengths.

Table 3-9. Summary port calls and voyage length by vessel type

		Port Calls (No. of Subvoyages)				Distance Traveled (nm)		
Ship Type / Sector	**Vessel Count**	**Low No. Port Calls**	**Median No. Port Calls**	**High No. Port Calls**	**Total Port Calls**	**Median Voyage distance Traveled**	**Median subvoyage Distance**	**Total distance traveled (all vessels)**
Cargo								
Bulk	243	1.0	2.0	14.0	579.0	739.3	362.5	209,871
Container	340	1.0	2.0	14.0	1,136.0	655.3	383.6	435,761
General Cargo	944	1.0	3.0	19.0	3,536.0	1,009.1	309.1	1,092,829
Heavy Lift	35	1.0	2.0	8.0	97.0	883.1	334.3	32,423
Reefer	28	1.0	2.0	7.0	69.0	909.1	363.3	25,068
Ro_Ro	237	1.0	2.0	14.0	691.0	1,492.7	914.8	632,115
Cargo Total	**1,828**	**1.0**	**2.0**	**19.0**	**6,109.0**	**911.8**	**397.5**	**2,428,079**
Tanker								
Bunkering	23	1.0	3.0	16.0	101.0	1,114.2	242.2	24,461
Chem/Oil	526	1.0	2.0	22.0	1,820.0	815.0	292.5	532,335
Crude Oil	130	1.0	2.0	7.0	336.0	802.4	363.3	122,060
LNG	37	1.0	2.0	6.0	76.0	571.1	496.4	37,728
LPG	83	1.0	3.0	10.0	287.0	1,027.9	350.1	100,481
Tanker Total	**799**	**1.0**	**2.0**	**22.0**	**2,620.0**	**818.3**	**311.9**	**817,066**
Support								
Crew Transport	6	1.0	1.5	6.0	15.0	834.9	344.8	5,173
Dredger	24	1.0	1.0	10.0	43.0	378.0	344.7	14,821
Nearshore Support	6	1.0	1.0	4.0	11.0	324.3	267.2	2,939
Offshore Platform	1	4.0	4.0	4.0	4.0	330.8	82.7	331
Offshore Supply	33	1.0	1.0	5.0	60.0	256.7	212.6	12,754
Offshore Support	108	1.0	2.0	6.0	206.0	145.8	205.6	42,360
Pilot	136	1.0	1.0	6.0	151.0	197.6	489.5	73,917
Tug/Towing	221	1.0	1.0	28.0	671.0	178.5	118.7	79,633
Support Total	**535**	**1.0**	**1.0**	**28.0**	**1,161.0**	**192.0**	**199.8**	**231,927**
Overall	**3,161**	**1.0**	**2.0**	**28.0**	**9,890.0**	**747.3**	**351.6**	**3,477,072**

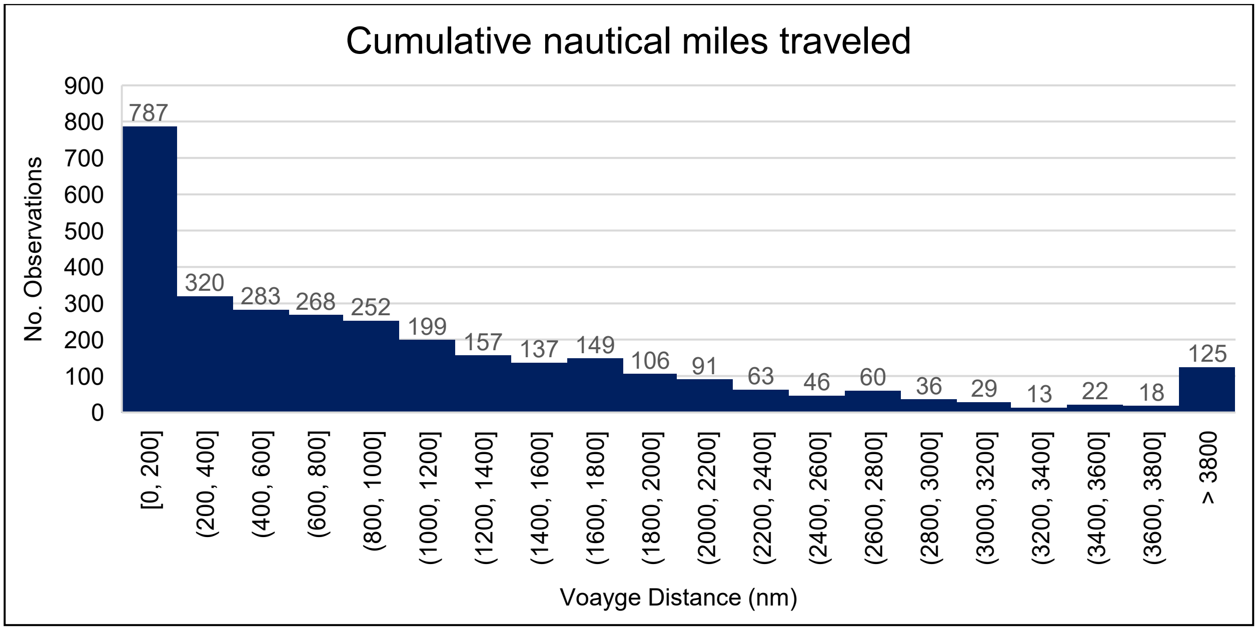


Figure 3-7. Histogram of cumulative nautical miles traveled per short-sea ship Jun 1-30, 2023

General cargo ships, bunkering tankers, and LPG tankers have the highest rates of utilization, visiting the most ports per voyage, on average. LNG and Crude Oil tankers travel the longest distance between ports likely due to the availability of import/export terminals. In most countries there are three or four ports that serve as hubs for the international trade of fuels and are closely aligned with refinery locations. These ships lack the destination flexibility of general cargo ships, which can berth at nearly every port in the dataset.

It should be noted that Ro-Ro vessels generally travel between two ports repeatedly. During the data cleaning process these pairs of ports were not differentiated if the traces listed one of the two ports are the primary destination. The average subvoyage distance is likely much lower and number of calls to port is much higher than reflected here. These vessels did, however, operate between 22 and 30 days, higher than the average vessel of other types, resulting in the comparatively high median voyage distance.

Support vessels have low median port calls yet seemingly high average nautical mileage for similar reasons. These vessels operate entirely within a single port yet are active for long hours. Pilot vessels, for instance, might navigate the same waterway 10-12 times in the same day assisting other ships.

The assumption uses the term “routine and repetitive.” Routine and repetitive indicate that ships are operating in a “liner” type service. These services are scheduled, routine, and are predictable. In actuality the data reveal four services: liner, charter, hub-and-spoke, and dedicated. Liner services have the appearance of scheduled, routine service to the same ports. This may occur in the same order or in “snaking” progression, starting in one order and ending in another. Within this dataset liner services were identified when at least part of the schedule (2 or more ports) were called to multiple times. Liner services, as well as subsequent service categories are shown in Figure 3-8.

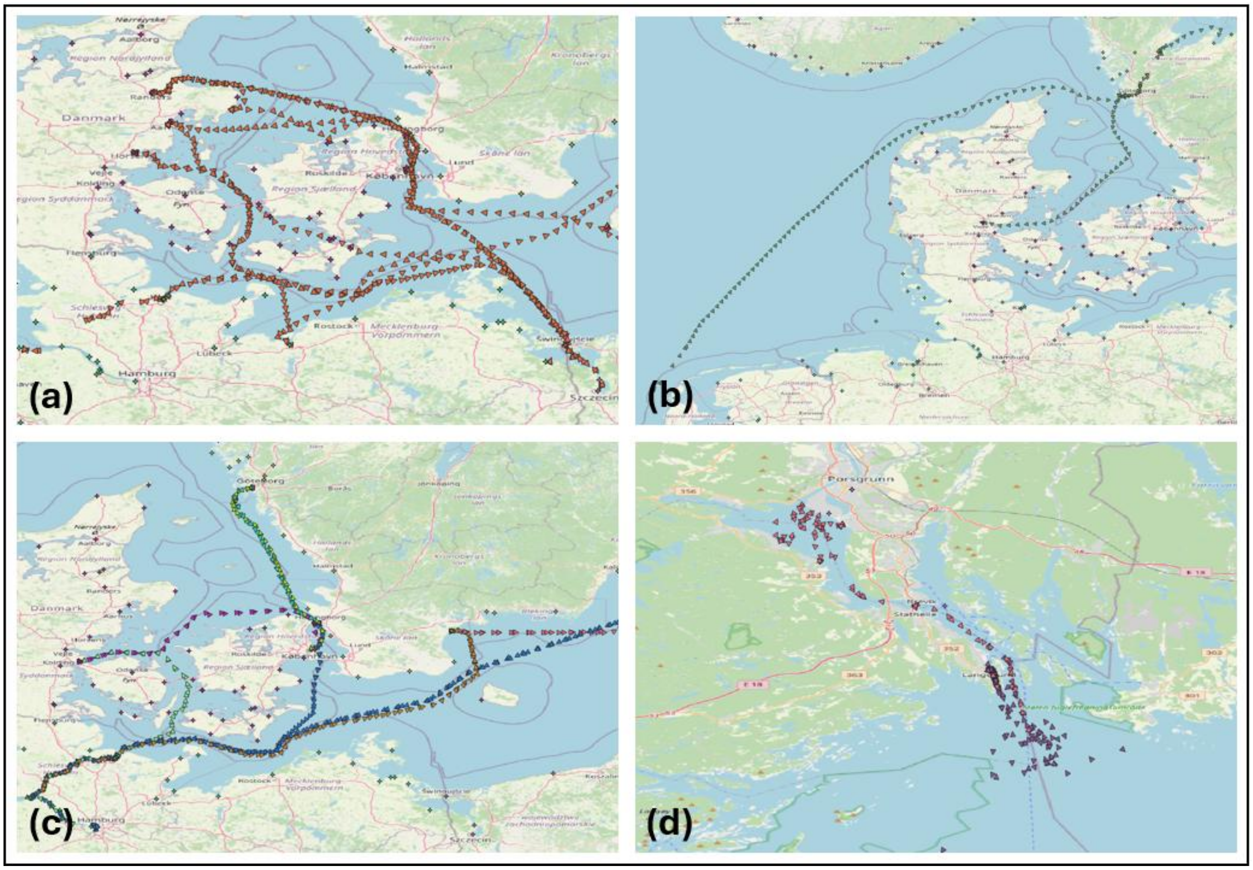


Figure 3-8. Sample voyage depictions of each service type (a) Liner, (b) Charter, (c) Hub-and-Spoke, (d) Dedicated Service

Charter services have no observable schedule or order of port calls. Often these services result in “For Order” or other variation in the AIS destination column. Some ships were identifiably charter services. Others visited ports in the study area for a few days of the observed period but departed to other SSS destinations. Still more appear in the study area for a brief period, arriving and departing after a few days. Each of these cases are treated as charter services but are potentially portions of longer liner services to France, Spain, Mediterranean destinations and others. Vessel Finder historic records, where all ports visited in a calendar year are listed, were used to verify these ships as SSS versus deep sea. Finally, ships that were moored or anchored within or outside of a single port were counted as charter services. The ships were active, but no additional destination data were available.

Hub-and-Spoke services are identified by a single port that serves as a base of operations. Ships depart this “hub” and make, most frequently, a single call or multiple calls before returning to the hub. The ship then departs for a wholly different port or series of ports. This service includes cargo and tanker vessels, but also crew transport, offshore supply/support, and dredging vessels.

Dedicated service is mostly representative of pilot and tug operations. These vessels remain in and around a single port for the duration of the study period. There are a few exceptions to the support craft. Bulk freighters and tankers sometimes shuttle freight between terminals. In one instance a tanker shuttled exclusively between offshore platforms (although it is likely that load was returned to port at some time. Interestingly, bunker tankers sometimes operated in dedicated service capacity but were more likely (76.4%) to shuttle bunkering fuel between ports in a charter or hub-and-spoke capacity.

Charter services and typically preferred due to the quick service speed, assuming availability of ship capacity. Table 3-10 shows the number of vessels categorized by service type as well as the median voyage speed for each vessel type and service. Most dry cargo and tanker vessels are categorized as charter vessels (71 and 72%, respectively). The number of dry cargo vessels operating in liner and hub-and-spoke services is close to even (13-14%). About one fifth of tankers operate in a hub-and-spoke network. This aligns with the import/export terminal concept as hubs mentioned previously. Additionally, many of these ships service offshore extraction sites in Norwegian, British, and Danish waters. Over 50% of support vessels service a dedicated port or waterway. Support vessels also conduct charter operations. Greater than half of these 110 vessels are tug/towing vessels that can be used to navigate complex coastal waterways and transport heavy equipment and barges.

The average speed of charter vessels is lower than both liner and hub-and-spoke ships. Charter vessels experience longer periods of station-keeping outside of ports before berth, which is included in the speed calculation. This pattern might be reflective of excess capacity in the shipping market as ships are waiting – sometimes for days – between loads. Future research can determine if the speeds while underway are statistically significantly different between service types.

Each vessel was assigned to a single service type. It is likely that some charter service vessels conduct liner-type or hub-and-spoke activities within their total service time, but the routes do not show this consistency. It’s possible, for instance, that a ship makes the same voyage between Gdansk, Poland and Tallinn, Estonia once a month, every month. This voyage takes approximately 3 days to complete and for the remaining 27-28 days the ship charters other cargos. In this study, that sample ship would be classified as a charter vessel.

Table 3-10. Vessels active in each service category

	Liner		Charter		Hub-and-Spoke		Dedicated	
Ship Type / Sector	**Vessel Count**	**Median Speed**	**Vessel Count**	**Median Speed**	**Vessel Count**	**Median Speed**	**Vessel Count**	**Median Speed**
Cargo								
Bulk	17	13.00	213	10.52	13	12.95	-	-
Container	38	14.25	209	12.25	92	14.46	1	3.48
General Cargo	81	11.89	751	10.92	97	11.41	15	3.33
Heavy Lift	3	12.44	27	13.68	1	7.10	4	1.69
Reefer	3	14.20	22	14.28	1	16.00	2	7.95
Ro_Ro	112	16.92	83	13.39	38	16.42	4	12.53
Cargo Total	254	14.57	1,306	11.33	242	13.44	26	4.86
Tanker								
Bunkering	4	7.97	7	8.66	7	8.50	5	1.49
Chem/Oil	36	11.95	405	10.72	80	12.20	4	1.58
Crude Oil	4	12.10	101	10.60	25	10.59	-	-
LNG	7	11.51	24	12.00	4	15.92	2	3.25
LPG	11	13.02	39	12.37	33	13.75	-	-
Tanker Total	**62**	**11.84**	**576**	**10.84**	**149**	**12.20**	**11**	**1.84**
Support								
Crew Transport	-	-	3	3.10	-	-	3	7.88
Dredger	1	12.00	8	7.94	1	10.93	14	3.84
Nearshore Support	-	-	2	4.84	-	-	4	4.74
Offshore Platform	-	-	1	4.97	-	-	-	-
Offshore Supply	1	1.03	7	7.34	19	3.70	6	5.92
Offshore Support	5	4.85	30	4.64	62	3.58	11	3.01
Pilot	16	5.57	-	-	-	-	120	4.61
Tug/Towing	15	5.24	59	6.47	19	4.47	128	2.19
Support Total	**38**	**5.39**	**110**	**6.00**	**101**	**3.85**	**286**	**3.49**
Overall	**354**	**13.11**	**1,992**	**10.89**	**492**	**11.09**	**323**	**3.55**

3.6.4 Cargo Tonnage, Ton-Mileage, and Capacity Usage

The addition of vessel design specifications to the AIS trace data allows for analysis of cargo transported by SSS vessels. This information is a key parameter in the emissions modeling phase of work. Table 3-11 provides a comparison of freight tonnage between the various types of cargo and tanker ships.

Container ships are responsible for the highest share of total freight tonnage transported (26%), followed by crude oil tankers (22%), general chemical/oil tankers (16%), and bulk freighters (14%). These four types rank in the same order for ton-mileage. Bulk freighters, crude oil tankers, and LNG tankers carry the most tonnage, on average, between ports. Each of these stats reflect 1) the comparatively large sizes of these vessels compared to all others, and 2) the nature the vessels’ cargo. Crude oil and other chemicals are volumetrically dense. Likewise bulk carriers that move metal ores, aggregates, and grains are also volumetrically dense. Container ships transport a range of containerized goods, which is lighter on a per M^3 basis, but most of these vessels are exceedingly large with the ability to carry thousands of ten-foot equivalent units.

Table 3-11. tonnage transported by vessel type

Ship Type / Sector	Count	Freight Tonnage (mil. mt)	Ton- Miles (mil. mt-nm)	Lower quartile Tonnage per O-D pair	Median Tonnage per O-D pair	Upper quartile Tonnage per O-D pair
Cargo						
Bulk	243	16.4	6,023.5	11,191.3	22,433.3	33,956.5
Container	340	29.4	11,161.7	6,536.4	10,916.1	28,302.0
General Cargo	944	10.7	3,965.5	1,134.9	2,166.8	3,457.9
Heavy Lift	35	1.4	464.6	6,003.5	8,580.4	16,326.4
Reefer	28	0.2	118.9	1,114.8	1,886.5	4,487.1
Ro_Ro	237	3.7	2,941.7	2,331.8	4,301.4	7,447.5
Cargo Total	**1,828**	**61.7**	**24,675.9**	**1,613.2**	**3,343.0**	**8,331.3**
Tanker						
Bunkering	23	0.2	69.7	479.3	1,404.9	2,920.1
Chem/Oil	526	17.9	6,589.5	3,143.9	5,825.2	12,264.5
Crude Oil	130	24.4	9,301.2	49,292.4	66,741.0	92,648.9
LNG	37	3.1	1,490.5	6,539.5	47,408.6	61,824.8
LPG	83	1.7	560.9	1,794.6	2,730.8	6,381.2
Tanker Total	799	47.3	**18,012.0**	**2,973.7**	**6,345.1**	**18,862.2**
Support Total	535	1.0	**220.6**	**52.9**	**130.0**	**464.8**
Overall	2,627	**110.0**	**42,907.5**	**1,402.3**	**3,340.0**	**9,097.9**

In a process described in Chapter 4 excess capacity can be calculated using draft as a stand-in variable. Table 3-12 shows the median load as a share of design capacity for each vessel type. The table also describes the limited vessels which sail either entirely unladen with cargo or overloaded compared to the design specifications of the ship. Tonnage is estimated cargo or freight tonnage. A portion of DWT for every ship is made up of wood and outfitting (W&O), power plant weight, ballast water, and fuel (57).

Few cargo-bearing SSS vessels sail unladen (1.9%). Even these ships only sailed unladen for a small share of their overall voyages. In most cases this occurs directly after long down-periods (possibly maintenance) or between loads for chartered ships. A greater share of ships travel overloaded (15%). Reefer vessels were the most likely to travel overloaded (25%) followed by Bulk Carriers (19%) and Chemical/Oil Tankers (19%). Ships can safely travel overloaded during periods of calm weather and seas. The rate of overloaded sailing in this dataset does not suggest patterns throughout the year as weather in the region is calmest during the early summer months. It is safer to travel about design DWT in the summer, but that does not mean it is an expected practice nor that this pattern does not exist outside of summer months.

Table 3-12. Overview of freight tonnage compared to design capacity by vessel type

Ship Type / Sector	Count	Median Load (%)	Unladen count	Unladen Time (%)	Unladen Distance (%)	Overload count	Median Overload (%)	Overload Time (%)	Overload Distance (%)
Cargo									
Bulk	243	70.40	-	-	-	46	3.53	10.77	10.13
Container	340	70.20	4	0.43	0.47	33	4.39	1.98	2.06
General Cargo	944	72.15	22	1.15	1.16	170	5.30	8.31	8.81
Heavy Lift	35	69.93	-	-	-	1	1.11	0.45	0.53
Reefer	28	84.29	-	-	-	7	8.42	11.74	13.36
Ro_Ro	237	69.75	18	5.49	5.29	37	8.76	3.85	3.52
Cargo Total	**1,828**	**71.34**	**45**	**1.44**	**1.43**	**294**	**5.41**	**6.78**	**6.95**
Tanker									
Bunkering	23	81.75	-	-	-	4	9.51	8.61	7.28
Chem/Oil	526	74.31	-	-	-	98	4.51	6.12	6.97
Crude Oil	130	65.80	-	-	-	4	2.18	1.34	1.45
LNG	37	75.30	1	2.70	2.70	-	-	-	-
LPG	83	63.46	2	2.41	2.41	5	7.62	1.69	1.81
Tanker Total	**799**	**71.71**	**3**	**0.38**	**0.38**	**111**	**4.75**	**4.67**	**5.22**
Support									
Dredging	24	57.81	-	-	-	-	-	-	-
Offshore Supply	33	74.03	3	9.09	9.09	-	-	-	-
Offshore Support	108	78.99	3	2.78	2.78	14	11.29	10.43	9.92
Support Total	165	74.92	6	3.66	3.96	14	11.29	10.43	9.92
Overall	**2,792**	**71.64**	**54**	**0.22**	**0.23**	**419**	**5.45**	**6.06**	**6.32**

3.6.5 Baltic-North Sea Region Freight Movement

This section explores the movement of ships between ports and countries. In the subsequent chapters the port of origin plays a critical role in determining emissions for a subvoyage. There are different approaches to considering the role of individual ports in decarbonization and this section explores some of those considerations.

Baltic-North Sea short sea shipping is dominated by a handful of key ports. Rotterdam, Hamburg, and Antwerp serve as the main hubs for international maritime trade for the entire continent. Gothenburg, Bremerhaven, Skagen, and Gdansk serve similar roles but more often in a continental sense. Table 3-13 shows the busiest ports and routes in the region based on total vessel arrivals or departures. Figure 3-9 graphically depicts some of the busiest routes repeated in the AIS data.

Despite the dominance of key ports in the western North Sea short sea shipping is still an important service for all Baltic-North Sea region countries. Figure 3-10 shows the total SSS vessel arrivals to each country in the region in June 2023. While the dominance of Rotterdam and Hamburg are still obvious, a few other details are revealed. Denmark, Norway, and Sweden are the next highly ranked countries. Though each country has relatively small populations, those populations are spread over expansive coastlines. Transportation by truck or train is not always the most efficient way to transport goods between those disparate population centers.

Table 3-13. Top ports and subvoyage O-D pairs based on vessel traffic

Rank	Port	Vessel Traffic	Port O-D Pair (independent of direction)	Vessel Traffic
1	Rotterdam, NL	536	Rotterdam, NL - Hamburg, DE	85
2	Hamburg, DE	391	Hamburg, DE - Antwerp, BE	79
3	Gothenburg, SE	363	Gothenburg, SE - Skagen, DK	64
4	Antwerp, BE	333	Hamburg, DE - Bremerhaven, DE	52
5	Bremerhaven, DE	241	Rotterdam, NL - Antwerp, BE	39
6	Skagen, DK	229	Antwerp, BE - Bremerhaven, DE	36
7	Gdansk, PL	216	Rotterdam, NL - Bremerhaven, DE	33
8	Rostock, DE	184	Ust-Luga, RU - Turkey (all dest.)	29
9	Amsterdam, NL	152	Rotterdam, NL - Gothenburg, SE	28
10	Klaipeda, LT	140	Esbjerg, DK - Offshore Locations	27
11	Szczecin, PL	130	Bremerhaven, DE - Gdansk, PL	26
12	France (all dest)	127	Brofjorden, SE - Gothenburg, SE	25
13	Gydnia, PL	125	Rotterdam, NL - Gdansk, PL	24
14	Kiel, DE	117	Gothenburg, SE - Copenhagen, DK	24
15	Aarhus, DK	109	Zeebrugge, BE - Bremerhaven, DE	21
16	Esbjerg, DK	108	Great Yarmouth, GB - Offshore Locations	20
17	Immingham, GB	88	Gdynia, PL - Klaipeda, Lithuania	20
18	Riga, LV	84	Rotterdam, NL - Teesport, GB	20
19	Mongstad, NO	78	Skagen, DK - Tallinn, EE	19
20	Helsingborg, SE	71	Aberdeen, GB - Offshore Locations	19

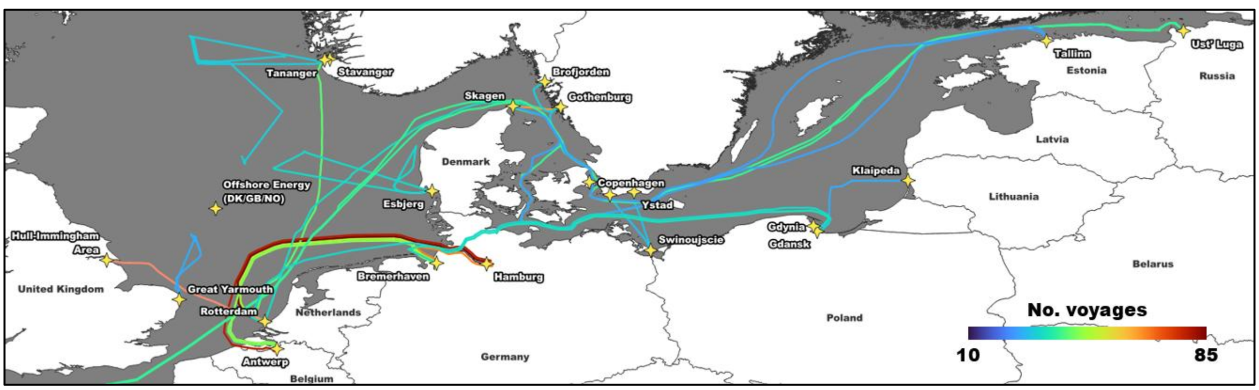


Figure 3-9. Top SSS vessel routes

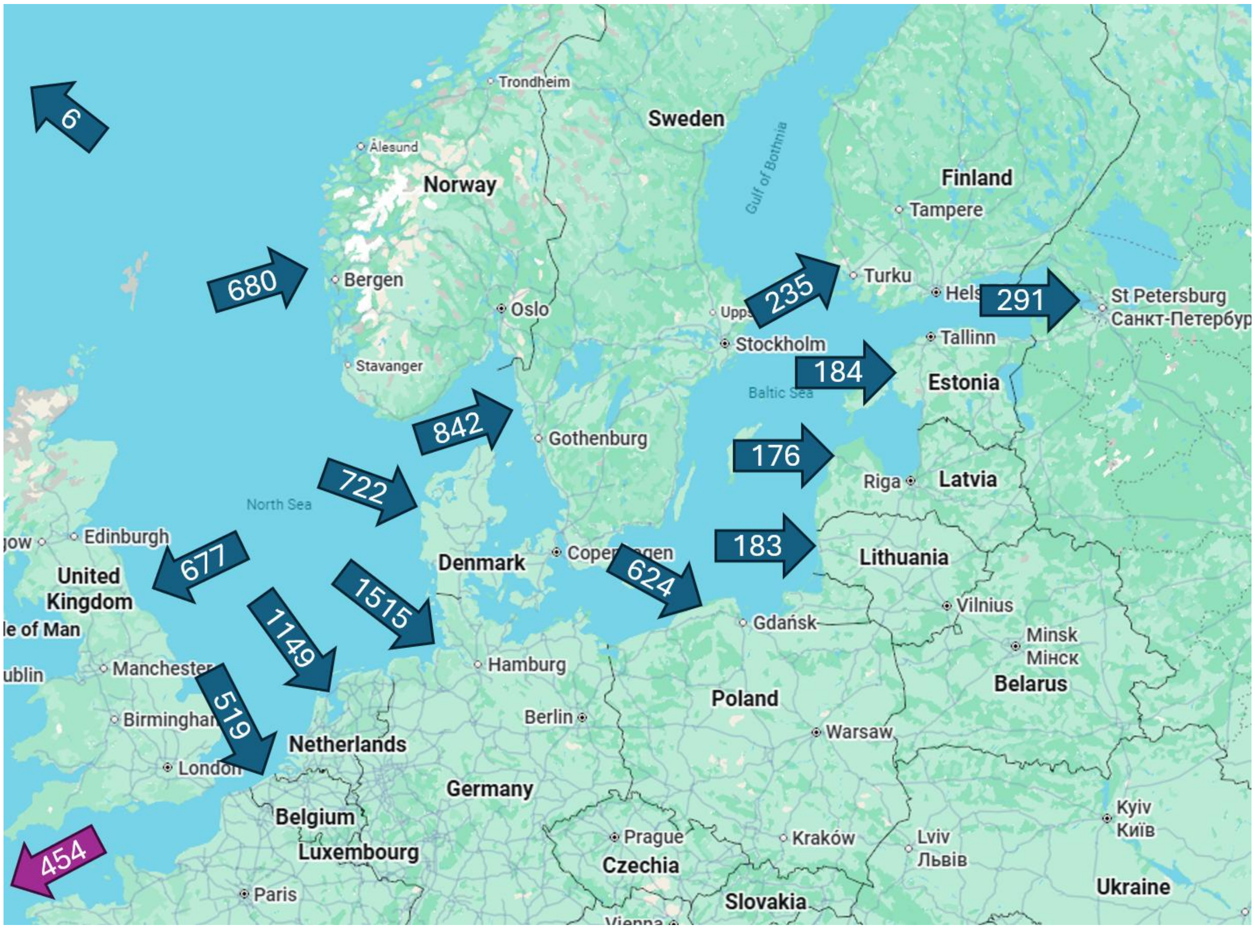
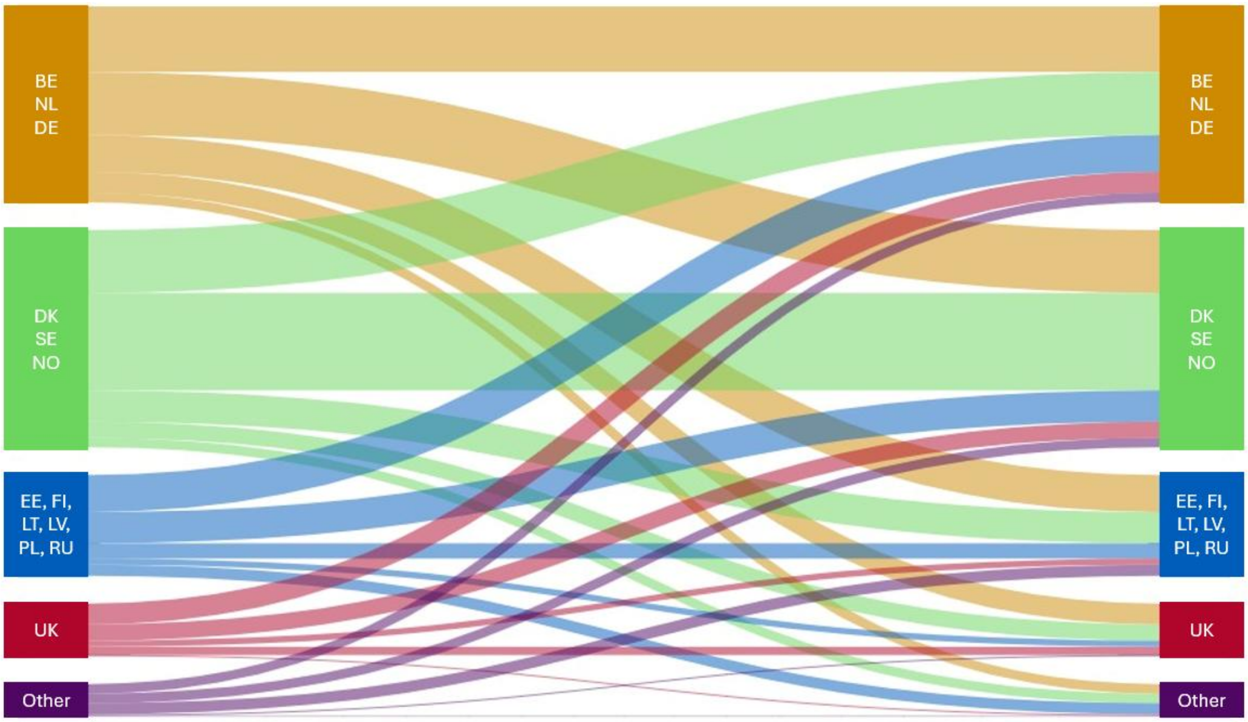


Figure 3-10. Total SSS vessel arrivals by country.

Figure 3-11 expands the arrival description by pairing origins with destinations. Countries are categorized by geographic location: Western North Sea countries, Nordic countries, Baltic Sea countries, the UK, and other European ports outside the region. Nordic countries experience high intraregional ports of call counts due to the number of pilot and tug vessels operation in the Oresund and within the constraints of fjords. Ro-Ro vessels contribute to this intraregional movement as well, especially between Sweden and Denmark. Smaller cargo and tanker vessels also visit multiple ports multiple times in these countries, more than any other in the study area. Comparing flows of total ships in Figure 3-10, this pattern is confirmed.

The “other” to “other” count appears anomalous, however the AIS coverage does extend to France in rare instances and France-to-Spain voyages are recorded. Additionally, there are a few Turkey-to-Turkey ships that register. The time spent in the North Sea are registered as “for order” and cargo does is not necessarily transferred to or from a Baltic-North Sea country.



BE: Belgium	NO: Norway	LV: Latvia	GB: United Kingdom
NL: Netherlands	SE: Sweden	LT: Lithuania	Other: France, Irelands, Portugal Spain, Turkey, etc.
DE: Germany	EE: Estonia	PL: Poland	
DK: Denmark	FI: Finland	RU: Russia	

Figure 3-11. Bi-directional flow of ships between sub-regions

Finally, the relatively low number of ships to and from the Baltic subregion does seem low. The AIS data show ships sailing to and from the proximity of Russia, but the destination is registered as “Baltic for Order” and the AIS traces disappear (i.e., the transponder might be turned off) during the approach to Russia. At the time of this study Russian trade was under internationally sanctions, indeed some of those “Baltic for Order” ships were individually under sanction. It is entirely possibly that other ships are misclassified or absent from the dataset entirely causing this study to undercount Russian trade. The share of ships involved in Russian trade classified as deep-sea rather than short sea is higher than most other countries with the exceptions of Belgium, Netherlands, and Germany. These shares are driven by the ports of Antwerp, Rotterdam, and Hamburg, respectively.

A better measure of trade flows that ports of call might be cargo tonnage. Figure 3-12 shows a similar Sankey diagram for tonnage. In this diagram, the share of trade from the Baltic subregion increases driven by 1) crude oil tankers to and from Russian, and 2) bulk freighters from Poland.

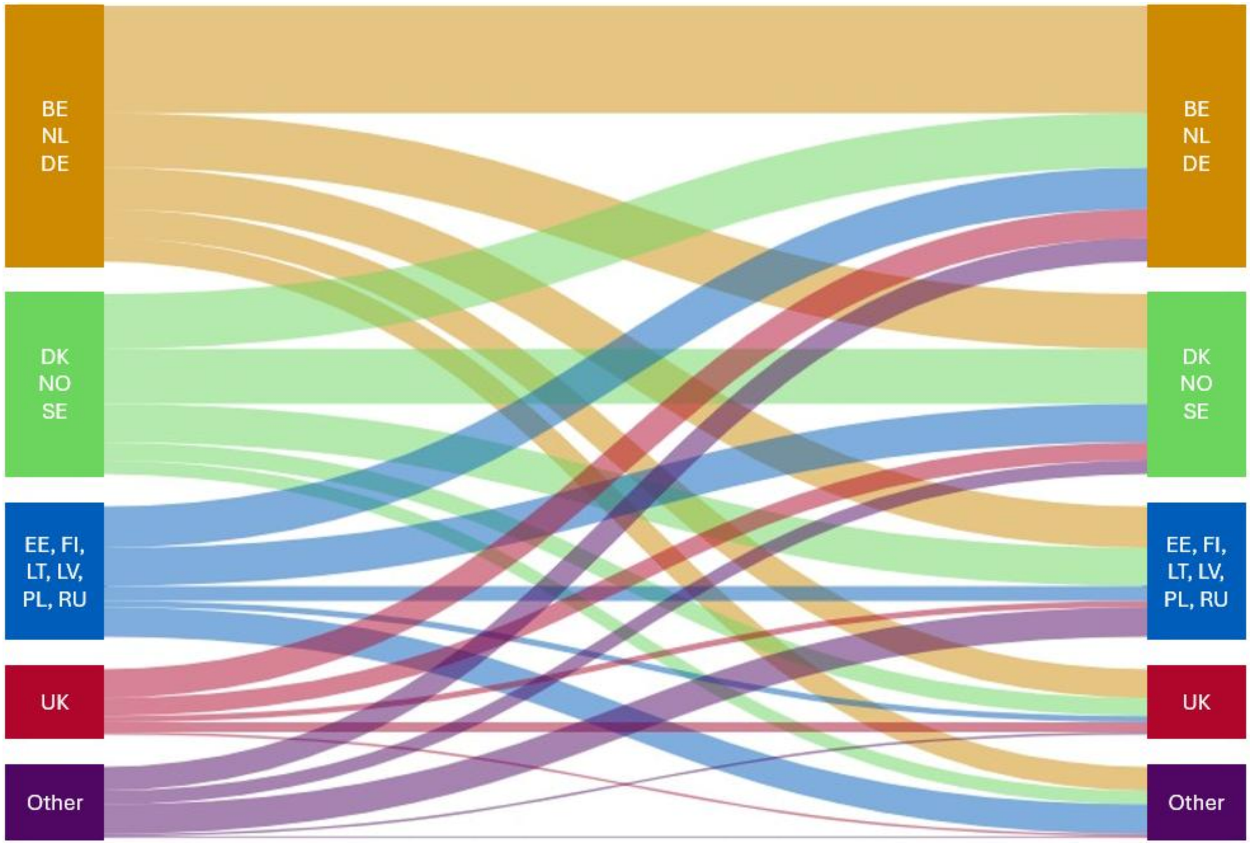


Figure 3-12. Bidirectional flow of cargo tonnage

Finally, the flow of freight between Baltic-North Sea region countries and key extra-regional partners France, Italy, Portugal, Spain, and Turkey are explored in Figure 3-13. France and Spain are the biggest partners for most regions, but this does not show the full SSS story. Many of these ships might be participating in liner services with other ports of call succeeding these two countries. However it is clear that bulk freight service between Poland (Gdansk and Szczecin specifically) operates in a liner capacity with outbound and inbound trips recorded.

The Turkey-Baltic subregion tonnage is an interesting case. Turkey is an oil producing nation, but still imports the majority of its domestically used oil. The majority of Baltic-Turkey trips are between the latter and Russia. They may be oil or other products. Despite sanctions, Turkey has either remained an important trade partner even with shared access to the Black Sea, or Turkish ports are being used as fake destinations for Russian products with the destination being changed outside of the study area.

The United Kingdom has a relatively low share of SSS with these major partners. This could be because major ports: Liverpool, London, and Southampton specifically are outside the study area and the true level of traffic is not captured. The majority of ships sailing to and from those ports simply do not enter the North Sea. Felixstowe, Immingham, and Tilbury handle freight originating from the study region: offshore oil and gas, paper products, and manufactured goods from Germany.

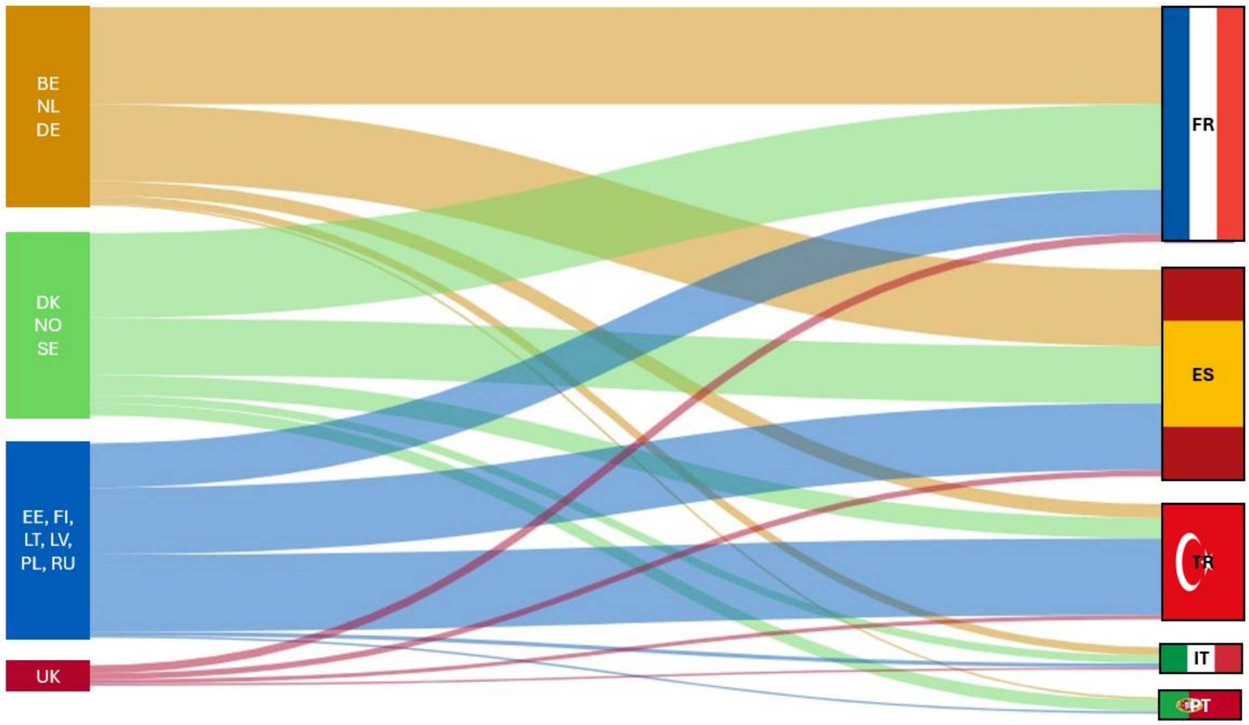


Figure 3-13. Bidirectional flow (tonnage) between Baltic-North Sea subregions and extra-regional SSS partners

3.7 Discussion

SSS vessels in the Baltic have different activity patterns than ocean-going ships. The main services offered by ocean-going vessels are charter and liner. Chartering is when a company enlists the dedicated service of a vessel for a proscribed period of time. Liner services have regular ports of call on a regular schedule. Both of these services appear to exist in Baltic-North Sea short sea shipping as well, but another pattern emerges, too. That is a hub-and-spoke style service where a vessel visits a few or many ports from a single home port.

The hub-and-spoke network shows in multiple forms. First, is petroleum products distribution. Tankers frequently travel between a major export or import terminal (e.g., Murmansk, Russia; Stavanger, Norway; Antwerp, Belgium; and Skogen, Denmark) and singular destination ports before returning to the main terminal. This occurs with crude oil products, LNG, bunker fuels, and other petroleum-based chemicals. The second form is offshore support and supply. Most of these support and crew vessels travel between a single home port (e.g., Aberdeen, UK; Peterhead, UK; Tananger or Bergen, Norway; Vlissingen, Netherlands; and Esbjerg, Denmark) and multiple offshore oil, gas, or wind farms. The third and final instance relates to dry freight. There are frequent dispatches of vessel from Gdansk, Poland (likely steel and other heavy industrial products). Fertilizer is a known commodity from central Norway (5). Rotterdam, Antwerp, and Hamburg also act as clearing houses for various freight types: container, bulk, and reefer. Ships transport goods and materials from these ports more often make multiple ports of call before returning to one of these three major import/export hubs.

The final example is an expected outcome. Ports with less cargo throughput act as feeder ports for Hamburg, Rotterdam, and Antwerp. At the latter ports freight is consolidated (or broken down) and exported to other markets. Many of the ships identified as ocean-going or deep-sea appear in the dataset around these three ports.

It's important to note that many ships are not dedicated to SSS. There are numerous vessels (Maersk, Denmark-flagged container ships) that participate in SSS for the 3-month study period but are routinely used for deep sea trips. For instance bulk carriers transport freight throughout the region for a period of three months, but the final destination in the July dataset is Brazil, Canada, or India. Similarly, inbound ships appear in May rounding the Faroe islands, suggesting an origin in the United States or Canada. These ships then remain in the Baltic-North Sea region for the study period, traveling between 2-4 ports.

3.8 Conclusions

This chapter discusses the structure of short sea shipping (SSS) in the Baltic-North Sea region. Using historic AIS trace data, the vessels involved in SSS were identified and categorized. This is a reproducible result useful for SSS identification in other regions of the world or for identification of other sectors.

Assumptions about short sea shipping include that vessels are smaller and older than deep-sea vessels, operate in routine patterns, and operate at less than full capacity utilization were not confirmed in masse. SSS vessels are slightly older, on average, but only by a year or two. SSS vessels are also smaller, on average, but again this difference is small. It is shown that most SSS vessels do not operate in routine schedules or between the same ports. Rather, over 50% of vessels demonstrate characteristics of charter services. Finally, SSS did demonstrate low-capacity utilization. The average for the entire fleet was around 75%.

The work described in this chapter is instrumental in the succeeding chapters. Characterization of SSS vessels and their voyage behavior allows for an accurate emission estimate of the industry. The services identified also provide a tool for emissions analysis.

Chapter 4: The short sea shipping fuel-cycle emissions model

4.1 Abstract

Maritime emissions are often estimated either for an entire fleet of vessels operating in a study area (71,72), or for a singular ship's voyage in proof-of-concept modeling (45,49). Both are useful, but disaggregated, industry-based and operation-based estimates can prove more useful to policymakers working to reduce climate impacts. This research develops a modified fuel cycle emissions model for ships to estimate the total emissions impact of short sea commercial shipping in the Baltic-North Sea region. Only about half of cargo and tanker vessels operating within the region can be categorized as short sea vessels, the rest typically operating in deep-sea capacities. These two categories diverge in the vessel duty cycle, number of ports of call, distance between calls, and ratio of cargo weight to total capacity. By estimating emissions for this sector future scenarios and propulsion systems can be compared to this baseline. This chapter explains the method for estimating SSS emissions: the Modified Fuel Cycle Analysis Model (MFCAM). Additionally this chapter describes the data requirements for the model and presents results of analyzing the trajectories of over 3,100 ships operating in the Baltic-North Sea in June 2023.

4.2 Introduction

The basis for this work is rooted in the Total Energy & Emissions Analysis for Marine Systems (TEAMS) model (45). In that study the authors modeled emissions from three U.S.-based sample ships: a passenger ferry, a tanker, and a container vessel. Total energy consumption was assessed considering all systems from propulsion to crew quarters power. The sources of fuel and refueling locations were known and the emission factors for those sources were available through the GREET platform (45). Typically fuel sales and individual purchases at bunker facilities are not publicly available, as is the case for the vessels considered in this study. Onboard power requirements for crew quarters, cargo refrigeration, and gas compression are also unknown. For that reason, the model presented in this chapter analyzes only the propulsion system requirements for each vessel. An additional unknown element is the total tonnage of freight on each vessel, but as will be demonstrated this can be modeled based on the observed draft of the ship compared to the design, or unladen, draft.

The requirements for the Modified Fuel Cycle Analysis are: 1) ship trajectories which includes speed, origin/destination information, and draft throughout the voyage; 2) unladen draft of each vessel; 3) powerplant size, which will provide the basis for calculating the energy required to propel a ship of a certain tonnage at a certain speed and acceleration; 4) the sources of fuel at each port of call; and 5) the distance between port of call and marine fuel refineries. Requirements 1-3 are used to calculate energy consumption and requirements 4 and 5 are used to generate emissions factors unique to each port. Emissions factors (EF) can vary according to the source of fuel as oil, gas, and refined petroleum imports are not uniform over the course of the year, and so the EFs are treated as a parameter with a range that is sampled over multiple interactions of the MFCA model run. The mathematical formulation of the MFCA will be described in section 4.4. A description of the data requirements and model parameters is included in section 4.3, below.

Key to the MFCA model calculations are emissions factors, or the amount of CO_2 released per unit of energy consumed. In this case, as with similar studies, the accepted unit of measure is g/KJ. Although an emissions factor of 92.4 g/KJ is the accepted standard this value does not fully consider 1) transportation emissions vary from country-to-country and even port-to-port and, 2) the source(s) of crude oil and natural gas are different for each country. Take the example of Latvian ports. Latvia imports the majority of its refined petroleum products – for this exercise we consider both HFO and MDO as refined products – either from Finland (15.6%) or Lithuania (63.7%) (73). The emissions factor for bunker fuels taken on by ships at Latvian ports should consider the transportation emissions of those fuels between the two refineries in Finland and Lithuania. Provided that distance is greater than the distance between the refineries and the ports in the respective countries, Latvia should have higher emissions factors.

This concept is further complicated by point 2: the source(s) of crude oil and natural gas are different for each country. Using the same example, we see Latvia might have higher emissions factors than Finland but lower than those of Lithuania. Finland imports nearly 80% of its crude oil from Norway (74). Lithuania's imports are more diverse: Saudi Arabia (39.5%), the United States (25.6%), Norway (23.2%), and the United Kingdom (9.1%). Based on transportation emissions, Lithuania will have higher emissions factors than Finland. With Latvia importing refined products from both countries, the median well-to-refinery emissions factor would fall somewhere between Finland's and Lithuania's plus transportation emissions. The quality and composition of crude oil is not universal globally. Saudi Arabia and other Arab states export four main types of crude oil, all of which vary in emissions factor based on molecular structure and extraction technique (75,76). Dixit et all (2023) quantify these variations in aggregated carbon intensity values for 20 oil producing nations (75).

Based on the carbon intensity of source fuels and transportation emissions between extraction site, refinery, and port bunkering facility, this study develops port-specific emissions factors for each of the three fuels (HFO, MDO, NG) used by ships in the 2023 AIS data. These factors are then applied to the energy consumption calculation in the MFCA model to calculate total emissions for each vessel voyage.

4.3 Data extraction and model parameters

The process for accounting for all data required to estimate emissions is shown in Figure 4-1. The identified nodes will be explained in detail in subsequent sections.

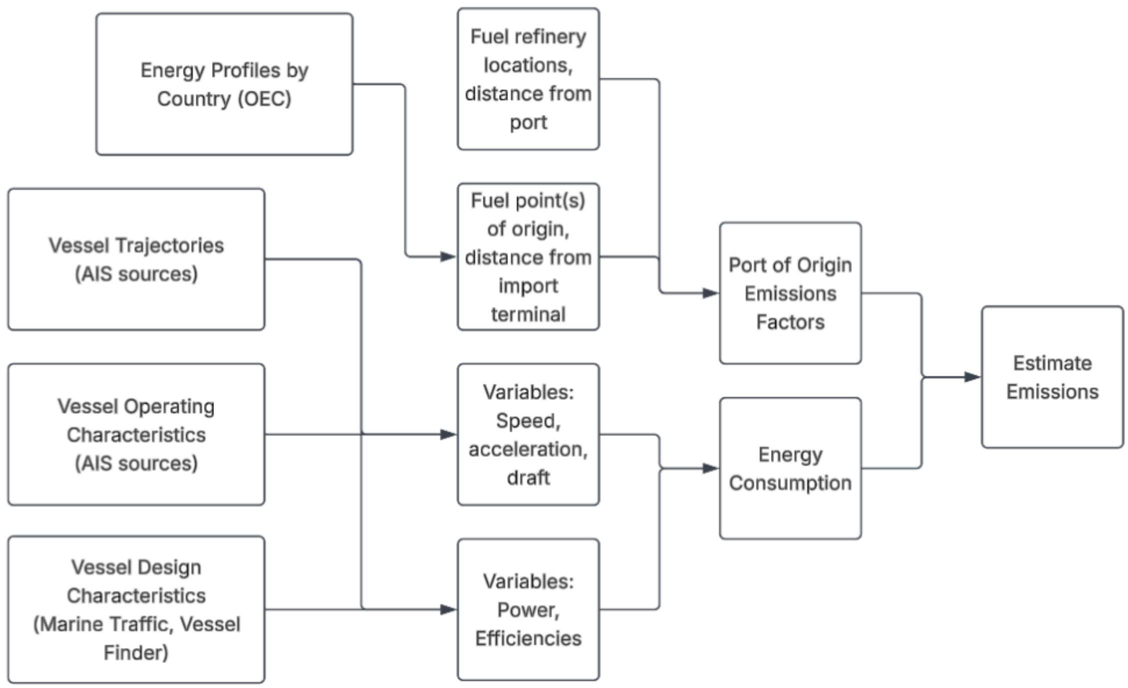


Figure 4-1. Data flow for emissions estimates

4.3.1 Vessel trajectories

Baltic-North Sea region SSS ship voyage data is based on historical AIS data explained in Chapter 3. The data were reduced to trajectories with observations in 30-minute intervals. This interval is adequate to determine changes in speed and average acceleration. Vessels change speed slowing, though course corrections can still occur within that time interval. Draft (or draught as it appears in the AIS dataset) information was included for over 95% of AIS traces. The remaining ~5% were interpolated based on predecessor and successor events. If the missing observation occurred between draft recordings equal in value it was assumed the missing value was also equal in value. If predecessor and successor were different the value was determined based on matching operating status. This scenario occurred most frequently when a ship was at berth or located within port waters. It is the loading and unloading of freight and refueling of the ship that causes changes in draft.

The destination port is almost always recorded in AIS traces. Exceptions existing when a ship does not have a scheduled load, in which case the destination will appear as “For Orders” or similar description. In those cases, a destination was assigned based on the next available destination. The port of origin is not recorded in AIS systems. As described in Chapter 3, the origin was determined by the predecessor destination. In cases where a predecessor did not exist, the May 2023 trajectories were included to extract the last destination. It should be noted that ports outside the Danish-Norwegian AIS network were aggregated by countries as the full vessel trajectory could not be observed. For example, container vessels frequently transit between North Sea ports and Spain. A vessel will depart Antwerp, Belgium or Hamburg, Germany, sail to one or more ports in Spain, and return to the study area to Rotterdam, Netherlands or Gothenburg, Sweden. It is not possible to determine the ports of call made in Spain using the existing data so the outbound journey and inbound journey are treated as two separate trajectories.

4.3.2 Unladen draft, displacement tonnage, and capacity usage of SSS vessels

Design draft, or unladen draft, data were collected from Marine Traffic (77), My Ship Tracking (69), Marine Public (78), and Vessel Finder (79). This information was not available for every freight carrier in the sample so design draft was interpolated based on class of the vessel. A container ship of dimensions 24m (beam) and 158m (LOA) built in 2018 and deadweight tonnage is assigned the design draft of a similarly sized and aged vessel. There are very few instances of unique ship dimensions within vessel types, but in those instances the draft approximation method outlined in (57) was used:

$$Draft = \frac{DWT}{C_B \times LOA \times Beam}$$

Where C_B is a standard coefficient for each ship type (e.g., Bulk Carrier = 0.820, Container Vessel = 0.600, etc.). Conversely, if design draft was know, this equation allows for DWT to be estimated. The key parameter for interpolation is build year because hull design has changed over time . The design draft for a vessel missing this information was selected from a similarly sized ship built within +/- 2 years. This is a multivariate approximation because ships have become larger and more efficient in terms of cargo capacity over time. A ship built in 1985 with the same dimensions would likely have a shallower draft due to the constraints of ports and canals.

Maximum drafts were collected from the same sources when available (69,70,78,79). For most vessels this was approximated using the maximum observed draft for each vessel type and dimension combination. The nature of LNG and containerized freight (lower density) precludes comparisons to bulk freighters, crude oil tankers, and heavy lift vessels. Maximum draft directly informs cargo capacity usage, or the observed percentage of total cargo tonnage onboard at the time of the AIS trace. Observed cargo capacity usage ($Cargo_{OB}$) was calculated using equation 1:

$$Cargo_{OB} = \frac{(Draft_{OB} - Draft_{ul})}{Draft_{max}} \times DWT \quad (1)$$

This study assumes the relationship between cargo tonnage and draft is linear similar to the findings of (80) and the ship design guidelines of (57), although as the ship hull flares from the keel upward, displacement decreases for each ton. For the purposes of calculating emissions intensity factors later in this chapter, the share of DWT attributed to cargo must be evaluated. DWT also includes wood and outfitting (W&O), power plant weight, ballast water, and fuel (57). W&O for ships over 100m LOA is equivalent to (LOA*beam)/3.57, for ships under 100m W&O is equivalent to (LOA*beam)/7.15 (57). Power plant weight is 0.075*design output power in kW plus 300 tons if the ship is greater than 75m LOA. Ballast water accounts for a maximum of 8-9% design DWT. An assumption is made that all cargo ships have at least some cargo onboard (minimum unutilized capacity = 40%) but ballast water was assumed to be 7% for all cargo vessels. Fuel reserves are assumed to be full at the outset of each subvoyage accounting for 3 (large cargo vessels) to 36% (dredging ships) of DWT.

4.3.3 Vessel power plant size

The sizes of a ship engines, henceforth "powerplants," were again scraped from Marine Traffic (77), My Ship Tracking (69), Marine Public (78), and Vessel Finder (79) indexed by the vessel's MMSI designation. Powerplants are rated by total power output measured in kW. Similar to draft power plants vary according to vessel dimensions, tonnage, and age. Missing power plant sizes were determined using ordinary least squares (OLS) linear regression models for each ship type.

The operating characteristics and cargo capacity of each ship type vary widely enough to warrant multiple models for the best fit to the independent variable, 'Power Plant Size (kW).' Summary information for two ship varieties, heavy lift vessel and crude oil tanker are shown below (Tables 4-1 and 4-2). Build year, length, width, gross tonnage (a measure of volumetric cargo capacity), and dead weight tonnage were the most frequently statistically significant independent variables, though width was not significant in several models. Some of these variables have the appearance of collinearity but do not. Length and width, for instance: width is determined by the waterways through which a ship sails rather than gross tonnage specifications, from which length is often determined.

Table 4-1. OLS Model for Heavy Lift Vessels (No. = 47)

Dependent Variable	Power plant size (kW)		R-squared	0.79220
			Adj. R-squared	0.75510
	Coef	Std error	t	P>|t|
Constant	177465.121	100695.298	1.570	0.128
Build year	-90.731	50.687	-1.790	0.084
Length (m)	69.311	28.704	2.415	0.022
Gross Tonnage (m^3)	0.361	0.130	2.783	0.009
Deadweight tonnage (tonnes)	-0.191	0.093	-2.063	0.048

Table 4-2. OLS Model for Crude Oil Tankers (No. = 167)

Dependent Variable	Power plant size (kW)		R-squared	0.73357
			Adj. R-squared	0.72519
	Coef	Std error	t	P>|t|
Constant	233432.567	74099.465	3.150	p < 0.001
Build year	-117.647	36.663	-3.209	p < 0.001
Width (m)	-205.576	100.911	-2.037	p < 0.001
Length (m)	75.871	22.560	3.363	p < 0.001
Gross Tonnage (m^3)	0.337	0.063	5.364	p < 0.001
Deadweight tonnage (tonnes)	-0.116	0.030	0.030	p < 0.001

4.3.4 Marine fuel sources

An underlying assumption of the MFCA model is that ships refuel at each port of call. In practice, the onboard fuel storage capacity of most observed ships exceeds the consumption for the observation period. This means most ships likely refueled once or twice, but the location of refueling is unidentifiable from the AIS trace data. The method by which emissions factors were determined for each port is described in section 4.4. This section explains the contributing dataset(s).

Marine fuel is assumed to be representative of the overall crude, refined petroleum product, and natural gas imports of each country. That is, the share of crude oil imported to a study country (e.g., Denmark or Belgium) is equal to the share of marine diesel refined from crude oil in Denmark or Belgium. These data were collected from the International Energy Agency (IEA) country-specific energy system overviews (81) and the Observatory of Economic Complexity (OEC) country-specific petroleum profiles (82). The former details the total share of petroleum or natural gas energy consumption from domestic sources. Norway, the United Kingdom, Denmark, Poland, and countries in the study area extract oil, but not exclusively for domestic use. For instance, Norwegian oil production is almost seven times greater than domestic consumption, yet only 24.1% of this consumption is met by domestic sources. The balance is imported from other countries including the United States (50.1%) and Nigeria (17.1%). Table 4-3 shows the major import partners for a sample of the Baltic-North Sea region countries and percentage share of domestic consumption contributed by each partner.

Table 4-3. Crude oil consumption for sample Baltic-North Sea countries by country of origin (%)

Country of Origin	Denmark	Finland	Germany	Norway	Sweden	United Kingdom
Domestic Production	43.6	0.0	3.0	24.1	0.0	60.4
Algeria	1.1					1.9
Angola					0.7	
Brazil		5.8			0.3	
Canada				2.3		1.3
Denmark	Dom. Prod.				0.8	
Ghana					0.5	
Guyana	1.6	0.8	3.8		0.9	
Iraq			4.9			
Kazakhstan					0.6	
Libya			15.2		3.5	1.9
Netherlands			5.8			
Nigeria	2.5		5.5	17.1	7.6	2.2
Norway	12.0	79.6	10.6	Dom. Prod.	60.4	17.2
Saudi Arabia			5.0			
UAE			3.9			
United Kingdom	5.4	8.0	7.2	6.0	13.2	Dom. Prod.
United States	33.9	10.9	18.3	50.5	11.6	12.1

4.3.5 Major marine fuel refineries

Emissions factors calculated for this model vary based on the point of origin for crude oil and natural gas as well as the locations of import terminals and oil refineries that produce marine fuels. Oil and gas terminals were identified using the Ship Next Port database, which describes the available terminals at each port (83). Refinery locations were identified through the Concawe "Refinery and Biorefinery Sites in Europe" map (84). Figure 4-2 shows the locations of these sites as well as ports visited by the sample ships.

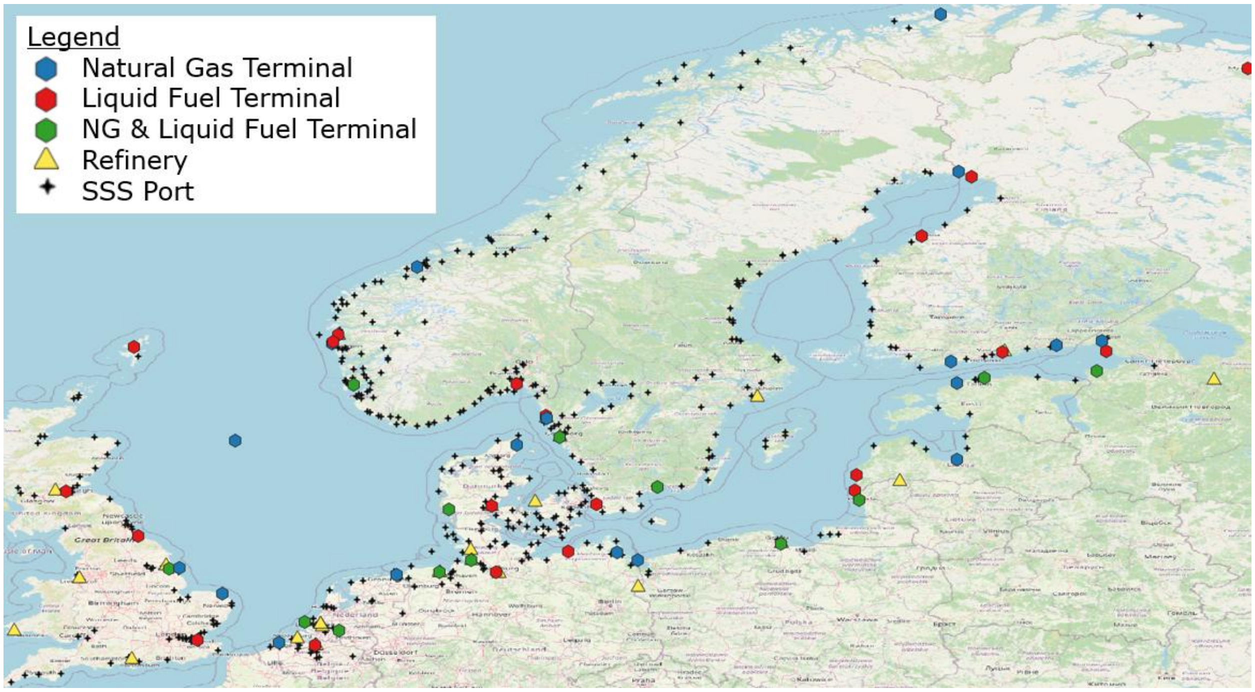


Figure 4-2. Baltic-North Sea Ports and Refineries

4.4 Methodology

The approach to calculating SSS emissions modifies an existing Fuel Cycle Emissions Model (Total Energy & Emissions Analysis for Marine Systems [TEAMS]) (45). CO_2 emissions factors were calculated for each port and vessel propulsion state similarly to the process for vehicle emissions estimates from (85). Using the vessel trajectories, loading, and powerplant information described in Chapter 3, energy consumption was calculated for each trip was estimated. The emissions factors were multiplied by the energy consumption of each voyage to estimate emissions per trip, which were summed to determine total emissions for Baltic Sea short sea shipping.

4.4.1 The Fuel Cycle Emissions Model

Equation (1) shows the basic format of the emissions model. $EM_{cm,i}$ represents the total CO_2 emissions *i*, from propulsion-related combustion (*cm*). In this portion of the research the fuels examined are based on the powerplant design of the ships investigated in Chapter 3. These are: marine distillates (MDO), heavy fuel oil (HFO) and natural gas (NG). $EF_{i,j,k}$ represents the CO_2 emission factor, or how many grams of CO_2 result from producing a MJ of energy given the propulsion powerplant design (*k*), specifically it's operating performance or efficiency and the powerplant size. These emissions factors vary according to where a ship refuels, how much cargo a ship is laden with, and the speed and acceleration of the ship. Emissions factors are multiplied by the energy consumption per operating state (e.g., idling, maneuvering, accelerating to cruising speed, cruising, decelerating, etc.) and summed across a vessel's full voyage or operating profile.

$$EM_{CO2} = \left(\sum_{Voyage} \sum_{Operating\ State} EF_{CO2,j,k} \times EC_{j,k}\right) \qquad (2)$$

$EF_{i,j,k}$ = CO_2 emission factor for process fuel *j* (MDO, HFO, LNG, etc.) with power plant design *k (size in kW)*

$EC_{j,k}$ = consumption of process fuel j using power plant design k

$$EC_{j,k} = ED \times SF_{j,k} \qquad (3)$$

ED = energy density of fuel type *j*

$SF_{j,k}$ = amount of fuel type *j* consumed during the operating state based on power plant design *k*

Emissions are calculated for each ship's complete voyage (tour) and each origin-destination ports of call (subtour) pairing. As noted previously, trajectories that involve a ship leaving the study area and returning were divided into separate trajectories. Ultimately emissions will be shown across vessel type, sub regions within the greater Baltic-North Sea region, and freight categories to provide a holistic overview of short sea shipping emissions.

4.4.2 Well-to-Tank Emissions Factors (EF)

Equation (1) shows that the type of fuel (j) and the type of propulsion power plant (k) are contributing factors to the emissions rate of vessels. The emissions factor, EF – or the amount of CO_2 (g) produced per KJ of energy consumed – can be further divided into feedstock emissions and combustion emissions (see equation (3)). Feedstock, also known as Well-to-Tank (WTT), emissions are those relating to discovery, extraction, refinement, transportation, and storage of the fuel and its component materials. Previous studies have identified that MDO and HFO transportation accounts for 20-24% of feedstock emissions (3-4% of total emissions) and processes (extraction, refinement, etc.) account for 76-80% of feedstock emissions (12-13%)(45,49). The NG emissions contributions for transportation are 48-56% of feedstock emissions (6.5-7.5% of total) and for processing are 44-52% of feedstock emissions (6-7% of total) (45,49). Other fuel types, including biodiesel, ammonia, and methanol were excluded from this study because they did not appear in the vessel list observed in the AIS data.

$$EF_{WTW} = EF_{WTT} + EF_{TTW} \qquad (4)$$

In this model the WTT emissions factors were calculated for each port. A major assumption is that bunkering, or storage, of fuel and therefore refueling services are available at every port. In practice this is likely not the case. Shippers often contract with bunkering companies and refuel regularly at the same or a series of ports of call, all with the same supplier. However, almost all cargo ports in the Baltic and surrounding area (Germany, Norway's North coast, Netherlands, and the United Kingdom) have bunkering capacity and offer either contract or spot pricing to shippers (83). Few port operators, shippers, or fuel suppliers report publicly where and when certain vessels refuel. For that reason, the WTT emission factor was based on the origin port in each subtour. This limitation ignores the fact that fuel brought on board at a port of call would mix with fuel already on board and that may have originated elsewhere. An exception to this rule relates to subtours involving some tankers, which directly burn some of the cargo oil or gas onboard to generate propulsion.

Combustion of fossil fuels is a standardized process and the combustion portion of WTW emissions (TTW) is a known quantity, varying only by a ship's powerplant, shaft, and propeller efficiencies. Discovery, extraction, refining, and processing (DERP) of fossil fuels are also known quantities. This work uses the established WTW emissions factors for each fuel, strips away combustion and refining, then calculates the transportation emissions for each port. Those emissions include transportation from the point of extraction (based on national import averages), transportation between import/export terminals, and transportation to the final bunkering location – the Baltic-North Sea ports included in this study. The accepted standard values of combustion and processing for each fuel are shown in Table 4-4.

Table 4-4. Standard emissions factor values for traditional maritime fuels (g CO_2 / MJ).

	WTW	Combustion		DERP	
Fuel	**emissions**	**Emissions**	**Share of WTW**	**Emissions**	**Share of WTW**
Heavy Fuel Oil	92.40	76.69 - 78.54	83.0 - 85.0	11.09 - 12.01	12.0 - 13.0
Marine Diesel	88.72	73.64 - 75.41	83.0 - 85.0	10.65 - 11.53	12.0 - 13.0
Natural Gas	65.81	56.27 - 57.58	85.5 - 87.5	3.95 - 4.61	6.0 - 7.0

The fossil fuel trade ebbs and flows with demand. Although home country imports of fuel were used to determine transportation emissions it is recognized that supply is not constant from each export partner. Transportation emissions were therefore calculated as a range to account for these fluctuations. A factor of +/- 10% was applied to the shares of oil and natural gas from each origin. Where fuels are imported and refined is also an unknown. It might be reasonable to assume that ports with an import terminal and a refinery in proximity to the port are supplied by that terminal and refinery (e.g., Vlissingen, Netherlands or Brunsbüttel, Germany). However, most countries have 2-3 major import terminals and 1-3 refineries compared to dozens of ports. Transportation between import terminal and refinery was assumed to be nearest neighbor, but transportation between refinery (or NG import terminal) and port was averaged across all refineries in a select country.

Table 4-5 shows the median transportation and WTW emissions for key ports. Emissions were estimated using WTW as a parameter in a simulation as opposed to the median or mean value. This process will be explained in Section 4.4.5. Figure 4-3 depicts the median WTT emissions factors for each of the three major fuels. WTT is shown here to compare NG to the two liquid fuels, HFO and MDO. Both the table and figure show transportation emissions factors that vary up to 9.5 g CO_2/MJ for liquid fuels and 18.0 g CO_2/MJ for natural gas. The standard transportation emissions for these fuels are between 2.0 and 6.0 g CO_2/MJ.

Table 4-5. Select fossil fuel emissions factors for Baltic-North Sea region ports (g/MJ)

	Heavy fuel oil (HFO)		Marine Distillate (MDO)		Natural Gas (NG)	
Country / Port	$EF_{transpo}$	EF_{WTW}	$EF_{transpo}$	EF_{WTW}	$EF_{transpo}$	EF_{WTW}
Belgium (median)	**0.85**	**90.01**	**0.85**	**86.46**	**4.37**	**65.57**
Antwerp	0.77	89.93	0.77	86.38	4.41	65.62
Denmark (median)	**5.52**	**94.69**	**5.52**	**91.14**	**10.79**	**71.99**
Skagen	5.65	94.82	5.65	91.27	10.50	71.70
Esbjerg	5.47	94.64	5.47	91.09	10.37	71.58
Copenhagen	5.49	94.66	5.49	91.11	10.87	72.07
Finland (median)	**4.34**	**93.50**	**4.34**	**89.95**	**14.34**	**75.55**
Helsinki	3.89	93.06	3.89	89.51	14.13	75.33
Kokkola	4.51	93.68	4.51	90.12	14.48	75.69
Tornio	4.84	94.01	4.84	90.45	14.72	75.92
Germany (median)	**6.42**	**95.59**	**6.42**	**92.04**	**8.22**	**69.42**
Hamburg	6.30	95.46	6.30	91.91	8.09	69.29
Bremerhaven	6.32	95.48	6.32	91.93	8.07	69.27
Rostock	6.44	95.61	6.44	92.05	8.27	69.47
Netherlands (median)	**7.54**	**96.70**	**7.54**	**93.15**	**3.09**	**64.29**
Rotterdam	7.39	96.55	7.39	93.00	2.97	64.17
Amsterdam	7.44	96.61	7.44	93.06	2.97	64.17
Vlissingen	7.42	96.58	7.42	93.03	3.23	64.43
Norway (median)	**9.73**	**98.90**	**9.73**	**95.35**	**10.33**	**71.54**
Oslo	9.01	98.18	9.01	94.63	9.67	70.87
Tanager	8.82	97.99	8.82	94.44	9.55	70.75
Tromso	10.38	99.54	10.38	95.99	10.97	72.18
Poland (median)	**2.52**	**91.69**	**2.52**	**88.14**	**2.04**	**63.24**
Gdansk	2.29	91.45	2.29	87.90	1.56	62.76
Gdynia	2.31	91.48	2.31	87.93	1.63	62.83
Swinoujscie	2.76	91.93	2.76	88.38	2.75	63.95
Russia (median)	**2.28**	**91.85**	**2.28**	**88.30**	**2.72**	**64.28**
Ust-Luga	2.06	91.22	2.06	87.67	1.52	62.73
St. Petersburg	1.91	91.07	1.91	87.52	1.76	62.97
Kaliningrad	3.14	92.31	3.14	88.75	4.45	65.65
Sweden (median)	**4.67**	**94.08**	**4.67**	**90.53**	**4.30**	**66.02**
Gothenburg	4.25	93.42	4.25	89.86	3.22	64.42
Ystad	4.59	93.76	4.59	90.21	3.77	64.97
Lulea	5.51	94.68	5.51	91.13	7.02	68.22

	Heavy fuel oil (HFO)		Marine Distillate (MDO)		Natural Gas (NG)	
Country / Port	$EF_{transpo}$	EF_{WTW}	$EF_{transpo}$	EF_{WTW}	$EF_{transpo}$	EF_{WTW}
United Kingdom (median)	**4.22**	**93.39**	**4.22**	**89.83**	**11.63**	**72.84**
Immingham	3.79	92.96	3.79	89.41	10.75	71.95
Felixstowe	3.96	93.12	3.96	89.57	11.05	72.26
Aberdeen	4.14	93.31	4.14	89.75	11.82	73.02
Baltic States (median)	**2.28**	**92.43**	**2.28**	**88.82**	**10.05**	**70.26**
Tallinn, Estonia	2.67	91.83	2.67	88.28	16.29	77.50
Klaipeda, Lithuania	7.19	96.36	7.19	92.80	20.14	81.34
Riga, Latvia	1.73	90.89	1.73	87.34	1.38	62.59
Other SSS Destinations						
France (median)	7.98	97.15	7.98	93.59	7.93	69.14
Italy (median)	8.00	97.17	8.00	93.61	9.80	71.01
Portugal (median)	10.30	99.46	10.30	95.91	20.59	81.79
Spain (median)	11.06	100.23	11.06	96.68	18.59	79.79
Turkey (median)	5.87	95.03	5.87	91.48	19.97	81.17

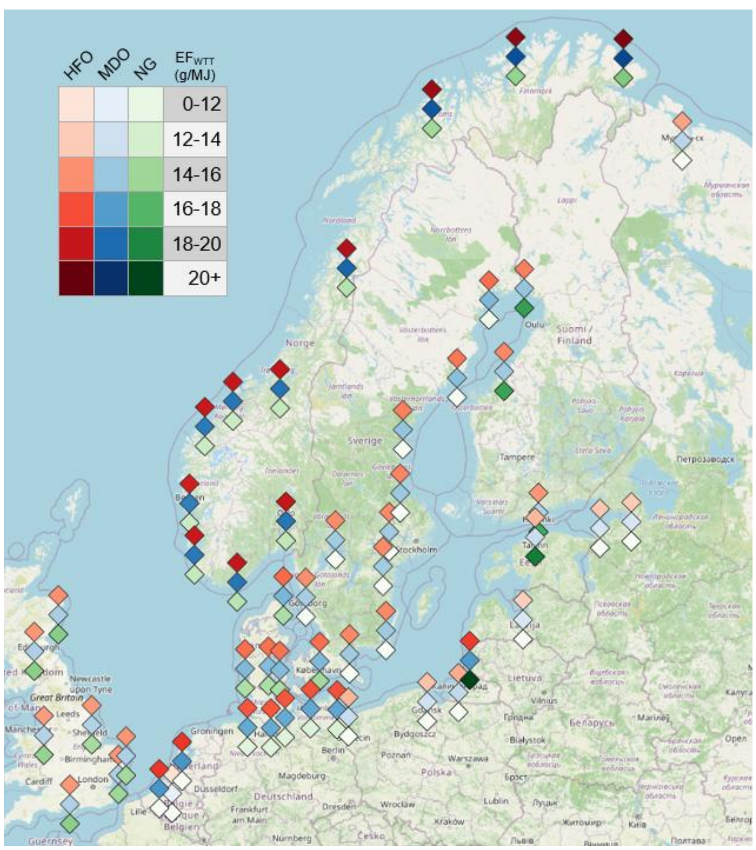


Figure 4-3. WTT emissions factors for various ports and fuels

4.4.3 Tank-to-Wake Emissions Factors (EF)

Combustion emissions, also known as tank-to-wake, are directly related to the energy or fuel consumed during a voyage but are contingent upon three elements: the propulsion state of the power plant, laden weight of the ship, and the overall efficiency of the vessel. Table 4-6 shows the propulsion states used for this model. Because short sea vessels must make constant course corrections and speed changes, the trajectory states reflect acceleration states in addition to the high-speed and low-speed cruising, precautionary, maneuvering, and idling states utilized by most fuel cycle or life cycle analyses (45).

Energy consumption varies according to the power output required to move the laden ship at a certain speed and acceleration. The relationship between speed and energy consumption and therefore emissions is strong. An increase in speed by 1% can result in an increase in emissions per nautical mile of 3% depending on oceanic conditions and route (86–88). Draught, or the distance between the waterline and the lowest point of the ship's hull, was used as a stand-in variable for cargo tonnage since AIS transponders do not report total tonnage. The relationship between draft and weight is essentially linear (57,80).

4.4.4 Calculating ship energy consumption

Ship power has a cubic relationship with speed through water (57,59). This work uses the widely accepted "modified admiralty formula" shown below as equation 5, where P(v,w) is the power required to move a ship of weight, *w*, at speed, *v*.

$$P(v,w) = m(A+w)^{2/3}v^n \quad (5)$$

A is the lightweight tonnage of the vessel, or it's total unladen design weight, *m* is a constant based on ship type, and *n* an exponent assumed to equal to 3 for merchant vessels (59).

There are two forms of efficiency included in this model: propeller efficiency and thrust efficiency. Propeller efficiency (EFF_{prop}) is the measure of proportion of thrust power that is delivered to propel the ship. This is impacted by ship architecture and varies from 60% (crude oil tankers to 75% narrow body general cargo ships (57). Thrust efficiency (EFF_T), really mechanical efficiency, is a measure of the proportion of heat energy converted to mechanical energy and power in the powerplant. For two- and four-stroke diesel engines this is about 40-50%. Without proper maintenance this efficiency can degrade over time which is accounted for at 1% per year for each year beyond the design life an engine is. From these efficiencies the power requirement at any speed is:

$$P_{in} = \frac{\left(\frac{P(v,w)}{EFF_{prop}}\right)}{EFF_T} \quad (6)$$

The vessel trajectories are parsed into 30-minute increments. Multiplying P_{in} by ½ provides the energy consumption ($EC_{j,k}$ from equation (4)) per trace in MJ. This final step is required because power is calculated in for one hour but traces are recorded every 30 minutes. It should be noted that power was calculated in kWh due to the design information available: all sources list powerplant size in kW. The half hour calculation occurred during this step, then power was converted to MJ (1 kWh = 3.6 MJ).

Calculating a ship's load from draft requires design information for each ship. With 3,161 SSS vessels in operation, however, it was tedious to search for engine and tonnage information for every vessel. There is no universal database for this ship information. Rather, ships were classified by their type (container, LPG tanker, etc.) and dimensions (length and breadth). Representative information for a subset of each vessel classification were gathered from four sources and verified between each of the four: Marine Traffic (77), My Ship Tracking (69), Marine Public (78), and Vessel Finder (79).

MarineTraffic records the unladen draft, allowing the model to calculate capacity utilization along each trip within a vessel's trajectory. Baltic Sea vessels typical operate between 40 and 80% capacity. In certain circumstances ships record drafts that exceed the maximum design draft. This poses structural and navigational hazards but does occur when origin and destination ports allow for the increased depth required. When this occurred in the current year and 2023 max draught on Vessel Finder were used to verify the values were not in error. Overages rarely exceeded 3% of design draft.

Using the proportion of deadweight tonnage plus the vessel's gross tonnage and the powerplant size, the power required to move the vessel at a calculated speed and acceleration was estimated. Combustion emissions rates were applied to these energy estimates according to the operating state similar to (89) for vehicles in a road network. The operating states are described below.

Table 4-6. Operating states for SSS vessels

Operating State	**Description**
Idling – at berth	Ship is within port facilities and speed = 0 knots. Engine load ≈ 2.5%
Station keeping	Ship is outside port, typically waiting for a berth or cargo. Speed ranges from 0-2 knots and acceleration is low.
Maneuvering	Ship is navigating coastal waters or within a port. Course changes and acceleration are required often.
Accelerating to slow cruise	Acceleration to speeds of 6-10 knots
Slow cruise	Near constant speed (6-10) knots. Engine power is typically in the 40-60% range.
Accelerating to fast cruise	Acceleration to speeds of 10-14 knots (16 max)
Fast cruise	Near constant speed (10-14 knots). Engine power typically in the 60-85% range.
Decelerating	Vessel is under power and reducing speed from slow or fast cruise.

While some ports and ships are equipped with shore power, it is assumed that for a berthed ship it is still under its own power. Most shore power stations have been designed for deep berths that typically service ocean-going craft.

4.4.5 Simulating results

Emissions from each vessel trajectory were calculated multiple times to account for variations in emissions factors and ship characteristics. Table 4-7 summarizes the simulation parameters.

Emissions factors can vary because 1) the exact origin of the fuel is unknown, 2) the exact location of refinement is unknown, and 3) the mode of fuel transportation is unknown. Emissions factors were calculated as a range and applied as a uniform distribution. Vessel characteristic parameters include hull efficiency, propeller efficiency, shaft efficiency, and powerplant efficiency.

Table 4-7. Emissions Simulation Parameters

Parameter	Range	Distribution
WTW Emissions Factors	HFO: 88.51 - 100.77, port specific MDO: 85.01 - 97.22, port specific NG: 60.64 - 95.20, port specific	Uniform distribution
Hull Efficiency	Ships built before 2000: 0.90 - 0.99 Ships built after 2000: 0.95 - 0.99	Triangle distribution
Propeller Efficiency	Ships built before 2000: 0.60 - 0.75 Ships built 2000-2010: 0.625 - 0.75 Ships built after 2010: 0.65 - 0.75	Triangle distribution
Shaft Efficiency	0.95 - 0.98	Triangle distribution
Power Plant Efficiency	HFO: 0.45 - 0.50 MDO: 0.43 - 0.48 NG: 0.35 - 0.45	Triangle distribution

Hull efficiency is related to both geometry and presence of extrusions on the hull. Ships built after 2000 have been designed for less drag to achieve higher speeds resulting in higher hull efficiency. Hull extrusions include barnacles and other sea life or damage from strikes. Ships must be scraped clean every 1-3 years, but it is unknown when any ship in the dataset was serviced in this way.

Propeller efficiencies were applied as a triangular distribution between 60 and 75%. Like hull efficiency these vary according to build year as propeller design has advanced since the early 2000s. Shaft efficiency, which measures energy loss between the power plant and propeller, was applied to all ships, regardless of build year. While machine rooms have moved toward the aft section of newer ships from midship, shortening the shaft, the literature has not suggested shaft efficiency has changed.

Power plant efficiency is also applied as a triangular distribution. Older ships would likely have lower efficiency ratings, but it is unknown what upgrades, maintenance, retrofits, or rebuilds these ships have undergone. Efficiencies were not assigned based on build years because the maintenance cycles of all ships are unknown. Each marine fuel: HFO, MDO, and NG is assigned a fuel-specific efficiency range.

Most modern ships use MDO for their primary propulsion. The Baltic-North Sea region is protected by an Emission Control Area (ECA) that prohibits high-sulfur content fuels like HFO. There are, however, ports in this study area that lie outside the ECA as well as ships that may flout environmental rules. Assignment of fuel type was determined by probabilities derived from the full dataset. MDO assigned with P=0.99, HFO with P=0.005, and multiple fuels (i.e., MDO used in national waters, HFO used at sea) also assigned a probability P=0.005. LNG-powered ships were exclusively deep-sea vessels. However, there were LNG tankers identified as dual-fuel tankers. Their powerplants can burn both MDO and NG. In these cases, each fuel was assigned a probability of selection of P=0.50

4.5 Results

SSS emissions can be evaluated according to the operations identified in the previous chapter. Overall emissions for all Baltic-North Sea region short sea shipping are presented first, then by shipping sector (dry freight, tankers, and support craft) and individual ship type, by service (liner, charter, hub-and-spoke, and dedicated operations), and finally according to nautical mileage. That final portion of the analysis will provide insight to how this model compares to similar models related to deep sea shipping. Ships that make multiple ports of call over short distances can result in higher emissions per nautical mile if transiting between ports requires acceleration and speed changes.

4.5.1 Total SSS and sub-sector emissions in the Baltic-North Sea region

The short sea shipping industry accounted for between 854 and 897 thousand tonnes of CO_2 emissions in month of June 2023. Table 4-8 shows the breakdown of those emissions by sector. Around two-thirds of emissions (67.8%) can be attributed to dry cargo vessels, which make up 57.8% of the sample fleet. Another 31.5% of emissions are produced by tankers, which are 25.2% of the sample. Unsurprisingly the emissions from support craft – which are smaller and lightly laden or not at all laden with freight – contribute a small portion of total emissions at 0.7%. Emissions by vessel type must be inspected to understand how various ships contribute to the total regional emissions.

Table 4-8. Simulated total emissions by sector during study period (tonnes CO_2)

		Total Emissions				
Ship Type / Sector	**Vessel Count**	**Minimum**	**Lower Quartile**	**Median**	**Upper Quartile**	**Maximum**
Cargo Vessels	1,828	581,079	594,455	594,623	594,792	608,184
Tanker Ships	798	267,278	274,325	274,680	275,030	282,244
Support Craft	535	6,430	6,593	6,600	6,607	6,770
All Vessels Total	**3,161**	**854,788**	**875,374**	**875,903**	**876,428**	**897,198**

4.5.2 SSS emissions by vessel type

As discussed in the previous chapter, dry cargo vessels subdivided into bulk, container, general cargo, Ro-Ro, heavy lift, reefer. Tankers are subdivided into general chemical/oil, crude oil, LPG, and LNG. Support craft include tugs, dredgers, bunkering tankers, offshore supply or support ships, pilot boats, crew transporters, and some nearshore tenders. The emissions for each of these ships are shown in Table 4-9.

Table 4-9. Simulated total emissions by vessel type during study period (tonnes CO_2)

Ship Type / Sector	Vessel Count	Total Emissions: Minimum	Lower Quartile	Median	Upper Quartile	Maximum
Cargo						
Bulk	243	86,573	88,604	88,660	88,715	90,753
Container	340	193,341	197,667	197,763	197,857	202,185
General Cargo	944	114,139	116,879	116,913	116,947	119,698
Heavy Lift	35	9,002	9,215	9,232	9,249	9,463
Reefer	28	4,260	4,348	4,356	4,364	4,451
Ro_Ro	237	173,742	177,579	177,698	177,820	181,651
Cargo Total	**1,828**	**581,079**	**594,455**	**594,623**	**594,792**	**608,184**
Tanker						
Bunkering	23	2,007	2,049	2,053	2,056	2,098
Chem/Oil	525	125,073	127,993	128,057	128,119	131,058
Crude Oil	130	100,169	102,541	102,628	102,711	105,082
LNG	37	22,031	22,991	23,300	23,640	24,876
LPG	83	17,963	18,506	18,628	18,740	19,349
Tanker Total	**798**	**267,278**	**274,325**	**274,680**	**275,030**	**282,244**
Support						
Crew Transport	6	139	142	142	143	146
Dredger	24	1,357	1,388	1,392	1,396	1,427
Nearshore Support	6	24	24	24	25	25
Offshore Platform	1	23	24	24	25	25
Offshore Supply	33	645	660	661	662	677
Offshore Support	108	3,162	3,244	3,248	3,253	3,335
Pilot	136	199	204	204	204	209
Tug/Towing	221	881	903	904	904	926
Support Total	**535**	**6,430**	**6,593**	**6,600**	**6,607**	**6,770**
All Vessels Total	**3,161**	**854,788**	**875,374**	**875,903**	**876,428**	**897,198**

The top contributors to Baltic-North Sea region SSS emissions are container ships (22.6%), Ro-Ro vessels (20.3%) general chemical/oil tankers (14.6%), general cargo vessels (13.3%), and Crude oil tankers (11.7%). Combined these vessels make up 82% of emissions and represent 69% of the sample fleet. The reasons each vessel type contributes so much varies. Container ships and crude oil tankers carry large shares of total tonnage (27 and 22%, respectively) across relatively few ships. These ships are large, carry large loads, and have high power demand. General cargo ships and chemical/oil tankers make up the majority of the Baltic-North Sea fleet. Each ship contributes less on a per-vessel basis, but the cumulative impact is significant. Finally, Ro-Ro vessels are inefficient compared to other vessels. These ships can be large but are overpowered compared to the cargo tonnage carried. The driver to Ro-Ro emissions is the overpowered propulsion systems for high speeds coupled with high per-vessel mileage during the study period (18.2% of all mileage).

It is worth noting bulk freighters contribute less than ships of similar average size (crude oil tankers and container ships). This is likely due to the low average speed of these freighters, which reduces power demand. Again, support craft contribute little to total regional emissions. Offshore support vessels, which tow or carry supplies and equipment to wind farms, oil rigs, and fuel exploration sites contribute about half of support craft emissions.

4.5.3 SSS emissions and other shipping metrics

There are a few additional metrics that help describe the state of shipping and that were explored in the previous chapter. Distance traveled, cargo tonnage transported, and a combination of the two: ton-miles (in this case ton-nautical miles) are used to measure overall activity. They can also be used to describe emissions *intensity*, a focus for maritime sustainability efforts. Table 4-10 describes the various emissions intensities by vessel type classification. The vessel mileage, cargo tonnage, and cargo ton-nm reflect total values across all ships of each classification.

Table 4-10. Emissions intensity by vessel type

Ship Type / Sector	**Vessel Count**	**Vessel Mileage** (nm)	**Cargo Tonnage** (ton)	**Cargo ton-nm** (mil ton-nm)	**Emissions (kg) per mil ton-nm**
Cargo					
Bulk	243	209,871	16,360,811	6,023.5	14.72
Container	340	435,761	29,375,363	11,161.7	17.72
General Cargo	944	1,092,829	10,749,281	3,965.5	29.48
Heavy Lift	35	32,423	1,351,067	464.6	19.87
Reefer	28	25,068	215,196	118.9	36.65
Ro_Ro	237	632,115	3,670,003	2,941.7	60.41
Cargo Total	**1,828**	**2,428,079**	**61,721,720**	**24,675.9**	**24.10**
Tanker					
Bunkering	23	24,461	227,948	69.7	29.43
Chem/Oil	526	532,335	17,904,771	6,589.5	19.43
Crude Oil	130	122,060	24,358,093	9,301.2	11.03
LNG	37	37,728	3,080,173	1,490.5	15.63
LPG	83	100,481	1,684,373	560.9	33.21
Tanker Total	**799**	**817,066**	**47,255,358**	**18,012.0**	**15.25**
Support					
Crew Transport	6	5,173	n/a	n/a	n/a
Dredger	24	14,821	235,593	74.7	18.63
Nearshore Support	6	2,939	2,680	0.4	56.74
Offshore Platform	1	331	11,494	1.0	25.71
Offshore Supply	33	12,754	113,428	20.1	32.89
Offshore Support	108	42,360	548,187	109.4	29.68
Pilot	136	73,917	n/a	n/a	n/a
Tug/Towing	221	79,633	105,203	12.4	73.04
Support Total	**535**	**231,927**	**1,021,159**	**219.6**	**30.05**
Overall	**3,161**	**3,477,072**	**109,998,237**	**42,907.5**	**20.41**

Crude oil and LNG tankers exhibit the highest emissions per nautical mile reflecting high power output over comparatively low total mileage. In the case of crude oil tankers this high-power output makes sense given the average size of the vessels. Only LNG tankers are larger, on average, than crude oil tankers. Therefore, the high emissions per nautical mile for LNG tankers is also explained. Bulk freighters and container ships rank third and fourth, respectively, based on emissions per mile. Again, these ships are large and in this case are responsible for high shares of tonnage per voyage, directly impacting the power output required.

Efficiencies in maritime shipping are achieved by maximizing cargo tonnage on board. Ships that specialize in heavy loads would therefore have lower carbon emissions intensity per ton. This is reflected by crude oil tankers (4.21 kg/ton), bulk freighters (5.42 kg/ton), and container vessels (6.73 kg/ton). The least efficient vessels are also identified: Ro-Ro vessels (48.42 kg/ton), reefer ships (20.24 kg/ton), and LPG tankers (11.06 kg/ton). LPG tankers and Ro-Ro vessels were identified in the previous chapter as having two of the lowest load-to-capacity ratios (60-70%), however reefer ships travelled at 85% capacity indicating the freight being transported is light in nature compared to containerized freight, dry bulk, and wet bulk materials.

Finally, combining the two previous metrics the most efficient vessels are identified as 1) crude oil tankers, 2) bulk freighters, and 3) LNG tankers. The least efficient ships are 1) Ro-Ro vessels, 2) reefer ships, 3) LPG tankers. General cargo ships have comparatively high capacity utilization rates but given the wide range of sizes, flexibility in cargo, and frequent port calls the emissions per ton-nm are also high. Likewise bunkering tankers have limited ability to achieve economies of scale given their comparatively small size.

4.5.4 SSS emissions by service

The most common ocean-going shipping services are “liner” and “charter”. Liner services are routine and scheduled. A ship, or a series of ships, make the same ports of call, in order, over a fixed period proscribed by the carrier. Charter services are similar to line-hauling in freight. A shipper enlists the service a ship and crew to carry a specific freight between specific origin-destination pairs. The period a charter extends can cover multiple trips between those pairs, but the schedule is less fixed, and the ship might operate between different origin-destination pairs immediately upon the conclusion of the charter.

Baltic-North Sea SSS experiences both service types as well as hub-and-spoke systems where voyages begin and end at the same port, but multiple ports might be visits sequentially, each with a return subtour to the “hub” port. “dedicated” services also exist. These are most frequently presented by tugs, bunkering tankers, dredgers, and other support craft, but some freight carriers also operate between terminals at a single port without entering the neighboring sea. How these services are identified for each vessel is explained in the previous section. The emissions and emission intensity metric for each service time and vessel category are shown in Table 4-11.

Charter service vessels were responsible for the highest level of emissions (54%) despite accounting for 63% of all vessels. This service was followed by Hub-and-spoke (26%) and Liner (21%) services. Hub-and-spoke vessels make up 15-16% of the sample fleet and Liner 11% of the sample fleet showing higher emissions intensity compared to Charter services. This is borne out by lower emissions per ton-mile metrics across all vessel sectors (cargo, tanker, and support). The lower carbon intensities indicate slower speeds, lower capacity utilization, or other factors that might reduce power requirements. Charter vessels do have lower capacity utilization (71%) than Liner (77%) and Hub-and-spoke services (75-76%), but the difference in speed is unknown. It was observed during cleaning that Charter vessels do station keep outside of major ports while waiting for the next load, but the average speed during a voyage varies considerably for all ship types.

Table 4-11. Emissions and emissions intensity by service type

Service Type	Emissions (tons CO_2)	Emissions per mil. ton-nm (kg CO_2)
Charter	**462,789**	**16.57**
Cargo	274,264	18.00
Tanker	186,200	14.78
Support	2,320	25.65
Liner	**186,384**	**39.59**
Cargo	167,950	45.06
Tanker	18,057	18.53
Support	293	42.87
Hub-and-Spoke	**224,512**	**21.98**
Cargo	151,767	26.63
Tanker	70,177	15.83
Support	2,569	31.95
Dedicated Service	**2,204**	**40.55**
Cargo	636	77.04
Tanker	150	36.25
Support	1,418	33.79

Dedicated service emissions intensity is the highest of all emission intensities. This service represents a small share of cargo and tanker ships. These ships demonstrate low speeds and low capacity utilization but rarely achieve cruising speeds at which two-stroke power plants achieve the highest combustion efficiencies.

4.6 Discussion

Short sea shipping is a complex industry of thousands of agents. While individual ships may make repeat voyages and visit the same ports on schedule, most ships fit into the charter description. These vessels operate without any discernable pattern. With periods of station keeping, waiting for loads, then rushing to make timely pick-ups it might be expected that charter vessels will exhibit higher emissions intensity. That is not the case as demonstrated in this study. On a per ton-mile basis, chartered vessels produce half the carbon intensity.

Overall emissions are driven by large ships with volumetrically dense goods. Container ships operate at high speeds and high-capacity utilization. These vessels produce the most emissions in the region. Bulk freight and crude oil tankers, which tend to be some of the largest vessels in the fleet, also exhibit high-capacity utilization and high emissions.

The emissions estimates of this study fall within reasonable bounds of other studies. Extrapolating over 12 months the model estimates emissions of the region at 7.8 – 10.5 million tons CO_2. The most recent HELCOM estimates for the entire Baltic Sea (all ship types, not just SSS) is 13.8 million. Another study calculated emissions at 44 million tons for the entire Baltic-Black Sea region. This study excluded more than half of all cargo vessels and all other ship types (sailing, cruise, fishing, etc.) and the estimates are in line with what is to be expected.

4.7 Conclusions

This work establishes the total climate impact of SSS by considering multiple characteristics established in the previous chapter: sector, ship type and service type. Emissions are determined by power output so capacity utilization, or the share of available cargo capacity occupied by cargo, speed, and ship size are all important determining factors. What this model incorporates that previous models do not are geographic-specific emissions factors. In this case port-specific emissions factors are developed that take into account the origin of various fuels as well as a individual port's distance from the import location and refinery.

A contribution of this work is a new model that uses open-source data to estimate emissions. Previous models relied on data provided to the researchers by shipping companies. The fueling location and volume of fuel as known. This information is not widely published. By using cargo volume/weight by way of draft in lieu of fuel consumption the emissions can be calculated.

Chapter 5: Application of short-sailing marine fuel-cycle emissions model using fuel cell propulsion scenarios

5.1 Abstract

The HMFCA model is adapted to estimate emissions from a portion of the industry adopting hydrogen fuel cell technology for propulsion. Four fuel cell technologies are analyzed, requiring distinctly different feedstocks, although fuel infrastructure remains relatively constant. Emissions factor ranges are developed for these feedstocks as the fuel source and energy required for conversion to H_2 or methanol can vary depending on the electricity mix available. The model is run as a simulation, randomly assigning vessel trajectories to the fuel cell technologies in 5% increments from 5 to 25%. The results of this chapter are compared to the baseline emissions estimate from Chapter 4 and further analyzed to uncover factors that influence the overall impact of such an industry conversion. At 5% adoption rate emissions are typically reduced by 1-1.5%. at higher rates this increases to up to 14% from baseline values from Chapter 4.

5.2 Introduction

Hydrogen fuel cells (HFC), also fuel cells (FC), are one technology that are considered a viable contender to reduce emissions in the maritime industry. There are advantages to FC technology over other alternatives. FCs do not require fuel combustion like biodiesel, dual fuel systems, natural gas, or methanol. Therefore, CO_2 emissions are not an automatic output of the chemical reaction. Hydrogen and other reactants that can be fed through a FC pose less risk to the environment and general public than nuclear fuels. These fuels are flammable but do not carry the risk of long-term contamination.

This chapter explores the total potential benefits to adopting fuel cell technology in Baltic-North Sea region short sea shipping. Four technologies are considered: Proton Exchange Membrane (PEMFC), Molten Carbonate (MCFC), Solid Oxide (SOFC), and Direct Methanol Fuel Cells (DMFC). A range of fuels is considered as well: hydrogen (H_2), methanol, natural gas, and MDO. The applicable fuels for each fuel cell are described later in this chapter. Ships that do not adopt fuel cell technology are assumed to use MDO and LNG at rates described in the previous chapter.

5.3 Methodological approach

The basis of this analysis is a further modified MFCA model. Emissions factors are calculated for hydrogen fuel cell inputs: hydrogen reformed from natural gas or biowaste, and methanol reformed from the same. The reformation of the fuel cell inputs from feedstock materials is energy intensive (40,90). Energy systems, namely electricity, vary in source: coal, natural gas, nuclear, wind, solar, hydro, and waste incineration being the most common sources. The emissions from these sources are considered in the WTW FC emissions factors based on the country in which a port is located. Due to the variation of feedstock options, lack of existing reformation infrastructure, and variations in daily electricity production emissions factors are treated as parameters in a simulation. The factors are calculated as ranges and randomly assigned to a vessel voyage or subtour corresponding to the port of origin.

5.3.1 HMFCA Simulations

The Hydrogen Modified Fuel Cell Analysis Model (HMFCA) is applied utilizing the simulation methodology described in Chapter 4. New fuel cell-related parameters are introduced including the fuel cell technology and related emissions factors, and adoption rate. Hydrogen fuel cell technology does not exist in a commercially viable form today. Adoption will be slow and require long-term testing of the available FC technologies. In this chapter adoption rate ranges from 5% to 25% of all vessels involved in SSS. Adoption is randomly assigned in each vessel to cover a variety of ships, DWT capacity usage, service types, and voyage distances. Selection considers the entire fleet rather than a percentage of each vessel type. Selection is also based on MMSI numbers so a ship's entire voyage (not simply a portion of a voyage or subvoyage) is selected. Fuel cell emission factors will be described in the next section. Table 5-1 describes the full set of simulation parameters.

Table 5-1. HMFCA Model Simulation Parameters

Parameter	**Range**	**Distribution**
FC adoption rate	5% - 25%, 5% increments	Random assignment
Fossil Fuel WTW Emissions Factors (g/MJ)	HFO: 88.51 - 100.77, port specific MDO: 85.01 - 97.22, port specific NG: 60.64 - 95.20, port specific	Uniform distribution
Fuel Cell WTW Emissions Factors (g/MJ)	PEMFC: 2.87 - 366.27, port specific MCFC: 8.38 - 308.54, port specific SOFC: 8.39 - 301.83, port specific DMFC: 8.39 - 374.53, port specific	Triangle distribution
Hull Efficiency	Ships built before 2000: 0.90 - 0.99 Ships built after 2000: 0.95 - 0.99	Triangle distribution
Propeller Efficiency	Ships built before 2000: 0.60 - 0.75 Ships built 2000-2010: 0.625 - 0.75 Ships built after 2010: 0.65 - 0.75	Triangle distribution
Shaft Efficiency	0.95 - 0.98	Triangle distribution
Fossil Fuel Power Plant Efficiency	HFO: 0.45 - 0.50 MDO: 0.43 - 0.48 NG: 0.35 - 0.45	Triangle distribution
Fuel Cell Efficiency	PEMFC: 0.50 - 0.60 (38,91,92). MCFC: 0.45 - 0.60 (34,37,38,91). SOFC: 0.45 - 0.60 (37,38,91). DMFC: 0.35 - 0.80 (36,38).	Triangle distribution

Simulations are run using a Monte Carlo-style strategy. Each combination of fuel cell technology (PEMFC, MCFC, SOFC, DMFC) and adoption rate (5-25%) were simulated 5,000 times. Adoption rate was applied on a ship-by-ship basis. If a ship is assigned to a fuel cell propulsion unit, the related emissions factors for every origin port are applied. The number of simulations allows for nearly all ships to be assigned a fuel cell technology at least once.

Emissions factor distributions are not fuel-specific. While the overall range for PEMFC, for instance, include water hydrolysis, coal gasification, natural gas steam reformation, and biomass conversion, the specific feedstock and related emissions factor range is not assigned as a parameter.

A few other assumptions apply to simulations. The same dataset, ship information, and cargo capacity utilizations are used. This assumes SSS will remain static in future years. Fuel cell technology is years away from introduction. It is reasonable to assume trade patterns and vessel utilization will change over time, but these factors cannot be predicted. It is also assumed that fuel technology would not be limited to the Baltic-North Sea region. Ships with origins and destinations outside of the region (e.g., France, Spain, Turkey, etc.) are included in the random assignment of fuel cell propulsion systems.

5.3.2 WTW Emissions factors for Fuel Cell Technologies

The calculation of WTW emissions for fuel cell technologies requires identifying the fuel or reactant, estimating the extraction and transportation emissions of that reactant's feedstock materials, estimating the energy required to produce the reactant (MJ/kg), estimating the emissions per MJ of energy in the production process, and finally, estimating the quantity of reactant required to produce the observed propeller power for a given vessel's trajectory. Since the input power is known from the MFCA model described in Chapter 4, the process can be described in reverse:

$$Q_r = \left(\frac{P(v,w)}{EFF}\right) \times \rho_{Er} \tag{6}$$

Where Q_r is the quantity of reactant, *i*, required in kg, *P(v,w)* is the propeller power required to move a ship of weight *w*, at speed *v*, EFF is the vessel efficiency including all parameters identified in Table 5-1 (hull, propeller, shaft, and power plant efficiencies), and ρ_{Er} is the energy density (MJ/kg) of the reactant, *r*, under consideration. From Q_r the upstream or WTT emissions are calculated:

$$EF_{PTTr,q} = Q_r \times EI_{r,q} \times EF_{grid} \tag{7}$$

Where $EF_{PTTr,q}$ are the emissions from producing reactant *r* by process q, $EI_{r,q}$ is the energy required to produce one kg of reactant r using process q, and EFF_{grid} is the emission factor of electricity grid at the reactant production site. Additional upstream emissions (EFF_{WTP}) including extraction and transportation are then added to $EF_{PTTr,q}$ to capture the full fuel cycle (WTW)

$$EF_{WTW} = EF_{PTTr,q} + EF_{WTP} \tag{8}$$

The four simulated fuel cell technologies allow for a variety of fuel types. A PEMFC requires high-quality, pure hydrogen. The higher-temperature MCFC allows for steam reformation of other fuels within the fuel cell system and can be fueled by natural gas, methanol, and MDO. The SOFC likewise allows for steam reformation but the structure of the system requires a liquid fuel: methanol or MDO. DMFC uses methanol only. Table 5-2 summarizes the fuels (*r*) that can be used by each fuel cell. Table 5-3 summarizes the available production processes (*q*) for each of those fuels.

Table 5-2. Useable fuels in each fuel cell type

Fuel Cell Type	Fuels / Reactants			
	H_2	Natural Gas	Methanol	MDO
PEMFC	✓			
MCFC		✓	✓	✓
SOFC			✓	✓
DMFC			✓	

Table 5-3. Feedstocks for each fuel type

Fuels	Fuel / Reactant Production Process					
	Extract + Refine	Water electrolysis	Coal Gasification	Dry Biomass Gasification	Natural Gas Steam Reformation	Wet Biomass Steam Reformation
H_2		✓	✓	✓	✓	✓
Natural Gas	✓					✓
Methanol			✓	✓	✓	✓
MDO	✓					

Fuel feedstocks can vary as widely as the fuel types used. Hydrogen can be produced during electrolysis of liquid water, gasification of dry biomass or coal, and steam reformation of natural gas or wet biomass. Methanol is typically produced during coal and dry biomass gasification, or steam reformation of natural gas and wet biomass. Natural gas can be extracted (sometimes requiring purifying or refining) or through steam reformation of wet biomass. Finally, MDO is a refined product of crude oil. Each of these processes are energy intensive in different ways, but the energy used, as well as the sourcing of the feedstock, to produce the fuels relate directly to the emissions factors. The energy intensities of fuel production are detailed in Table 5-4. These intensities are input at $EI_{r,q}$ in Equation 7, above.

Table 5-4. Fuel processing/refinement energy intensity (MJ/kg)

Fuels	Fuel / Reactant Production Process					
	Extract + Refine	Water electrolysis	Coal Gasification	Dry Biomass Gasification	Natural Gas Steam Reformation	Wet Biomass Steam Reformation
H_2		Low 177.30 High 253.30	Low 216.00 High 241.20	Low 57.60 High 118.80	Low 149.40 High 163.80	Low 180.00 High 252.00
Natural Gas	Low 2.27 High 9.90					Low 43.20 High 90.00
Methanol			Low 21.89 High 31.90	Low 37.80 High 46.08	Low 29.16 High 37.08	Low 11.99 High 20.02
MDO	Low 4.59 High 15.66					

In ideal conditions (temperature, pressure, water purity, etc.) the energy required to produce 1 kg of H_2 from water is 39.4 kWh (93). Modern electrolyzers can achieve an efficiency rating of 70-80%, but the current range of practical equipment is wider (56-80%) (93,94). The process of gasification can be used to produce syngas (synthesis gas) from solid or semi-solid materials like coal and biomass. This syngas, which can also be steam reformed from natural gas and methane, can then converted into H_2 and CO_2 through a water gas shift reaction (95). There are many gasification processes in use today with a typical conversion efficiency of 55-65% although experimental gasification processes have recorded efficiencies of greater than 75% (95–97).

Production of H_2 and other feedstock fuels is energy intensive. While many of the processes can be powered directly from natural gas turbines or on-site wind turbines and solar fields, for industrial-scale adoption of fuel cell technology the source of energy with the potential for lower emissions is the electric grid due to the increasing capacity of renewable generation, coupling a low-emission fuel with low-emission production. This assumption forms the basis for fuel cell reactant production. There are eight primary sources of electricity: four combustion-based power plants (coal, natural gas, and oil products, and biomass), two renewable resources (solar and wind), and three other low-carbon sources (geothermal, hydroelectric, and nuclear). The average emissions rates (g CO_2 / MJ electricity generation) are shown in Table 5-5. While the European grid has regional interconnections that share demand management (determining from what power plants or sources demand is being serviced) the accepted practice is to calculate grid emissions per country. Table 5-6 shows the average emissions per MJ consumed for each Baltic-North Sea region country.

Table 5-5. 2023 emission rates by electricity source (g CO_2 / MJ)

Electricity Source					
Combustion-based		Renewable		Low-Carbon	
Coal	250.0	Solar	9.7	Geothermal	17.5
Natural Gas	52.8	Wind	3.3	Hydroelectric	5.1
Petroleum	194.4			Nuclear	3.3
Biomass	63.9				

Table 5-6. 2023 Electricity production emission factors for Baltic-North Sea region countries and important SSS partners (g CO_2 / MJ)

Electric emission factors by country					
Belgium	41.7	Italy	69.4	Portugal	31.9
Denmark	21.1	Latvia	18.9	Russia	113.9
Estonia	149.4	Lithuania	21.7	Spain	38.9
Finland	9.2	Netherlands	71.1	Sweden	1.9
France	13.3	Norway	6.7	Turkey	115.7
Germany	88.9	Poland	165.0	United Kingdom	40.3

Similarly to fossil fuel emissions factors, transportation (WTT) emissions are also calculated for each source of feedstock. In addition to oil and natural gas countries of origin these new factors include transportation of coal from a range of trading partners for each country. Some countries including Denmark, Estonia, and Portugal have entirely phased out coal. In those cases, coal was not considered a feasible feedstock. Biomass (wet and dry) are not assumed to be produced in high enough quantities in every country to cover the energy needs of SSS. Finland, Sweden, and Norway rely on timber and wood exports. It is assumed these countries have adequate biomass sources for H_2 and methanol production. The Netherlands and France produce massive amounts of agricultural products that can also be relied on for biomass gasification or, after digestion of said biomass to produce methane, steam reformation . In smaller countries without major timber-related or agricultural exports the top trade partners of related products are used as the country of origin for biomass feedstocks.

Fuel cell emissions factors therefore include transportation and processing emissions. Table 5-7 summarizes the median emissions factors for each fuel cell technology. Fossil fuel WTW emission factors are shown for comparison. The table is not exhaustive but shows ports responsible for the most vessel traffic for each country or that reflect the range in emissions factors within a given country.

The most significant factor in fuel cell emissions factors is the electricity mix of the home country. Since grids are interconnected it is impossible to identify the source of electricity from each individual port. It is accepted practice to calculate electricity grid emissions for each country (or state in the United States). This country-specific electricity mix factors are applied to energy requirements to create the needed fuel(s) for each fuel cell technology.

Table 5-7. Fossil Fuel and Hydrogen Fuel Cell Median Emissions Factors for select Baltic-North Sea region ports (g/MJ)

	Fossil Fuels			**Fuel Cell Technology**			
Country / Port	**HFO**	**MDO**	**NG**	**PEMFC**	**MCFC**	**SOFC**	**DMFC**
Belgium	**90.01**	**86.46**	**65.57**	**68.83**	**53.17**	**52.16**	**60.57**
Antwerp	89.93	86.38	65.62	68.75	53.09	52.09	60.49
Denmark	**94.69**	**91.14**	**71.99**	**33.60**	**34.73**	**34.73**	**35.97**
Skagen	94.82	91.27	71.70	30.70	34.77	34.77	36.00
Esbjerg	94.64	91.09	71.58	33.74	34.61	34.61	35.95
Copenhagen	94.66	91.11	72.07	33.53	34.92	34.92	36.14
Finland	**93.50**	**89.95**	**75.55**	**27.76**	**25.49**	**25.49**	**25.49**
Helsinki	93.06	89.51	75.33	27.70	25.43	25.43	25.43
Kokkola	93.68	90.12	75.69	27.85	25.58	25.58	25.58
Tornio	94.01	90.45	75.92	28.03	25.76	25.76	25.76
Germany	**95.59**	**92.04**	**69.42**	**99.17**	**94.66**	**93.08**	**100.32**
Hamburg	95.46	91.91	69.29	99.05	94.49	92.96	100.20
Bremerhaven	95.48	91.93	69.27	99.09	94.51	92.99	100.25
Rostock	95.61	92.05	69.47	99.18	94.63	93.10	100.33
Netherlands	**96.70**	**93.15**	**64.29**	**81.31**	**71.26**	**72.78**	**73.34**
Rotterdam	96.55	93.00	64.17	81.24	71.18	72.65	73.31
Amsterdam	96.61	93.06	64.17	81.26	71.14	72.64	73.23
Vlissingen	96.58	93.03	64.43	81.33	71.33	72.71	73.39

	Fossil Fuels			Fuel Cell Technology			
Country / Port	**HFO**	**MDO**	**NG**	**PEMFC**	**MCFC**	**SOFC**	**DMFC**
Norway	**98.90**	**95.35**	**71.54**	**20.38**	**19.72**	**19.72**	**19.72**
Oslo	98.18	94.63	70.87	19.86	18.85	18.85	18.85
Tanager	97.99	94.44	70.75	20.36	19.03	19.03	19.03
Tromso	99.54	95.99	72.18	21.31	20.56	20.56	20.56
Poland	**91.69**	**88.14**	**63.24**	**204.16**	**185.67**	**182.20**	**207.08**
Gdansk	91.45	87.90	62.76	204.37	185.43	182.20	207.29
Gdynia	91.48	87.93	62.83	204.36	185.45	182.21	207.28
Swinoujscie	91.93	88.38	63.95	203.99	185.72	182.25	206.91
Russia	**91.85**	**88.30**	**64.28**	**158.96**	**135.05**	**132.49**	**162.35**
Ust-Luga	91.22	87.67	62.73	158.36	133.58	131.88	161.74
St. Petersburg	91.07	87.52	62.97	158.39	133.69	131.82	161.77
Kaliningrad	92.31	88.75	65.65	159.51	135.33	133.00	162.90
Sweden	**94.08**	**90.53**	**66.02**	**9.47**	**14.37**	**14.19**	**14.19**
Gothenburg	93.42	89.86	64.42	9.79	12.96	12.91	12.91
Ystad	93.76	90.21	64.97	9.97	13.36	13.31	13.31
Lulea	94.68	91.13	68.22	9.81	15.45	14.45	14.45
United Kingdom	**93.39**	**89.83**	**72.84**	**62.41**	**54.43**	**53.46**	**60.93**
Immingham	92.96	89.41	71.95	62.20	53.98	53.01	60.54
Felixstowe	93.12	89.57	72.26	62.13	54.11	53.14	60.64
Aberdeen	93.31	89.75	73.02	62.64	54.26	53.29	60.75
Baltic States	**92.43**	**88.82**	**70.26**	**69.50**	**31.29**	**30.84**	**77.82**
Tallinn, Estonia	91.83	88.28	77.50	198.54	169.61	166.00	202.98
Klaipeda, Lithuania	96.36	92.80	81.34	38.87	42.57	42.57	43.04
Riga, Latvia	90.89	87.34	62.59	34.10	28.49	28.71	30.43
Other SSS Destinations							
France	97.15	93.59	69.14	36.26	32.95	32.95	32.95
Italy	97.17	93.61	71.01	96.38	86.26	85.07	98.45
Portugal	99.46	95.91	81.79	48.68	52.74	52.74	54.83
Spain	100.23	96.68	79.79	67.24	57.52	57.52	62.44
Turkey	95.03	91.48	81.17	159.46	137.31	134.52	162.90

Figure 5-1 shows the range of emissions factors for a sample of countries. HFO, MDO, and natural gas have narrow emissions factor ranged based mainly on the fact that the majority of emissions are generated during combustion rather than extraction, transportation, or processing. The fuel cell emission factor ranges for Denmark and Sweden are also relatively narrow compared to Germany and Estonia. Each of these countries relies heavily on renewable resources for electricity production. Regardless of the origin of feedstocks, emissions remain low in these countries. Germany, while an oil and gas producing nation and one that has invested in renewable resources, has greater reliance on coal and natural gas power plants than Denmark and Sweden. Estonia's wide range of emission factors reflect an electrical grid reliant on coal and petroleum, but also low-carbon sources of NG and MDO that can be direct fed through molten carbonate or solid oxide fuel cells.

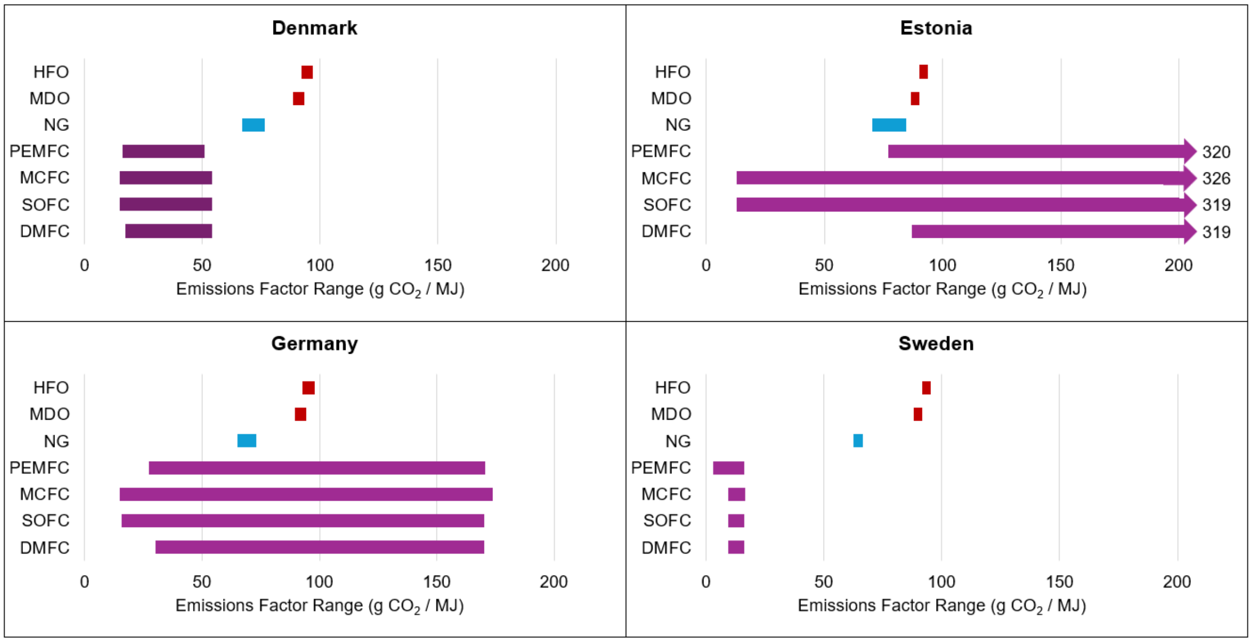


Figure 5-1. Country-based emissions factors for all marine fuel types.

5.4 Results

5.4.1 Total emissions and impacts of FC adoption

Almost all adoption scenarios for each of the four fuel cell technologies result in total emissions reductions. The exceptions are maximum fuel emissions values in the 5% adoption rate scenarios for all four fuel cell types and the maximum emissions in the 10% adoption rate scenarios of the proton exchange membrane fuel cell (PEMFC) and direct methanol fuel cell (DMFC). These values are outliers with the overall scenario ranges, but similarities can be observed. In these scenarios the assigned ships travel between countries with particularly high emitting electricity grids. These voyages include Russia↔Turkey, Poland↔Estonia, and any voyages to or from North African countries in the Mediterranean. Similarly, there are outliers in the positive (emission savings) direction. In these cases the assigned ships typically operate between ports in Sweden and Norway, for instance. This idea will be explored in more detail in Chapter 6. As the adoption rate increases the likelihood of a ship visiting countries or ports with low emissions factors increases. Table 5-8 shows the total change in emissions from the baseline (fossil fuels) in each adoption/technology scenario.

At maximum adoption (25%) the total emissions reduction ranges from 6.11 to 14.20%. This is a positive development for an industry searching for low-carbon solutions. While fuel cells do not appear to be a zero emission solution – % change from baseline should be around 25% if that were the case – the reductions are greater than alternative drop-in fuels currently being tested.

Table 5-8. Total emissions after FC adoption and comparison to baseline emissions

FC Technology & Adoption Rate	Low total Emissions (tons CO_2)	% Change from Baseline	Median total Emissions (tons CO_2)	% Change from Baseline	High total Emissions (tons CO_2)	% Change from Baseline
PEMFC						
5% adoption	852,368	2.72	868,410	0.89	883,739	-0.86
10% adoption	840,751	4.05	859,073	1.96	878,372	-0.24
15% adoption	828,538	5.44	850,437	2.95	872,603	0.42
20% adoption	815,895	6.89	840,859	4.04	866,154	1.15
25% adoption	803,217	8.33	832,105	5.04	860,370	1.81
MCFC						
5% adoption	848,958	3.11	864,809	1.31	880,275	-0.46
10% adoption	831,820	5.07	851,986	2.77	870,617	0.64
15% adoption	815,190	6.97	838,988	4.25	861,519	1.68
20% adoption	797,489	8.99	825,671	5.77	852,707	2.69
25% adoption	779,648	11.02	813,072	7.21	844,000	3.68
SOFC						
5% adoption	849,811	3.02	864,517	1.34	877,651	-0.16
10% adoption	831,846	5.07	851,809	2.79	869,833	0.73
15% adoption	813,005	7.22	838,821	4.27	861,909	1.64
20% adoption	799,002	8.82	825,948	5.74	853,386	2.61
25% adoption	785,840	10.32	813,022	7.22	845,213	3.54
DMFC						
5% adoption	851,035	2.88	868,476	0.89	883,765	-0.86
10% adoption	836,323	4.56	859,734	1.88	879,599	-0.38
15% adoption	821,822	6.21	850,257	2.97	874,943	0.15
20% adoption	808,729	7.70	841,400	3.98	867,573	0.99
25% adoption	795,672	9.20	832,228	5.02	859,993	1.85

Figure 5-2 shows the change of emissions reductions for three scenarios: 5%, 15%, and 25% adoption. Molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) have the highest potential for SSS emissions reduction. Two factors contribute to this finding. First is fuel flexibility. MCFCs can generate electricity from H_2, methanol, natural gas, or MDO. While emissions are produced during the extraction and processing of natural gas and MDO, those emissions are low per unit of energy produced compared to water electrolysis or coal/biomass gasification. SOFCs can use any liquid fuel – MDO and methanol being the most likely fuels – and while SOFC does not benefit from natural gas emissions rate, low emissions rates for MDO are accounted for. The second factor is potential for decoupling from the electric grid. The penalties for ships refueling in Estonia, Turkey, and other countries with few renewable resources are lessened when using these fuels.

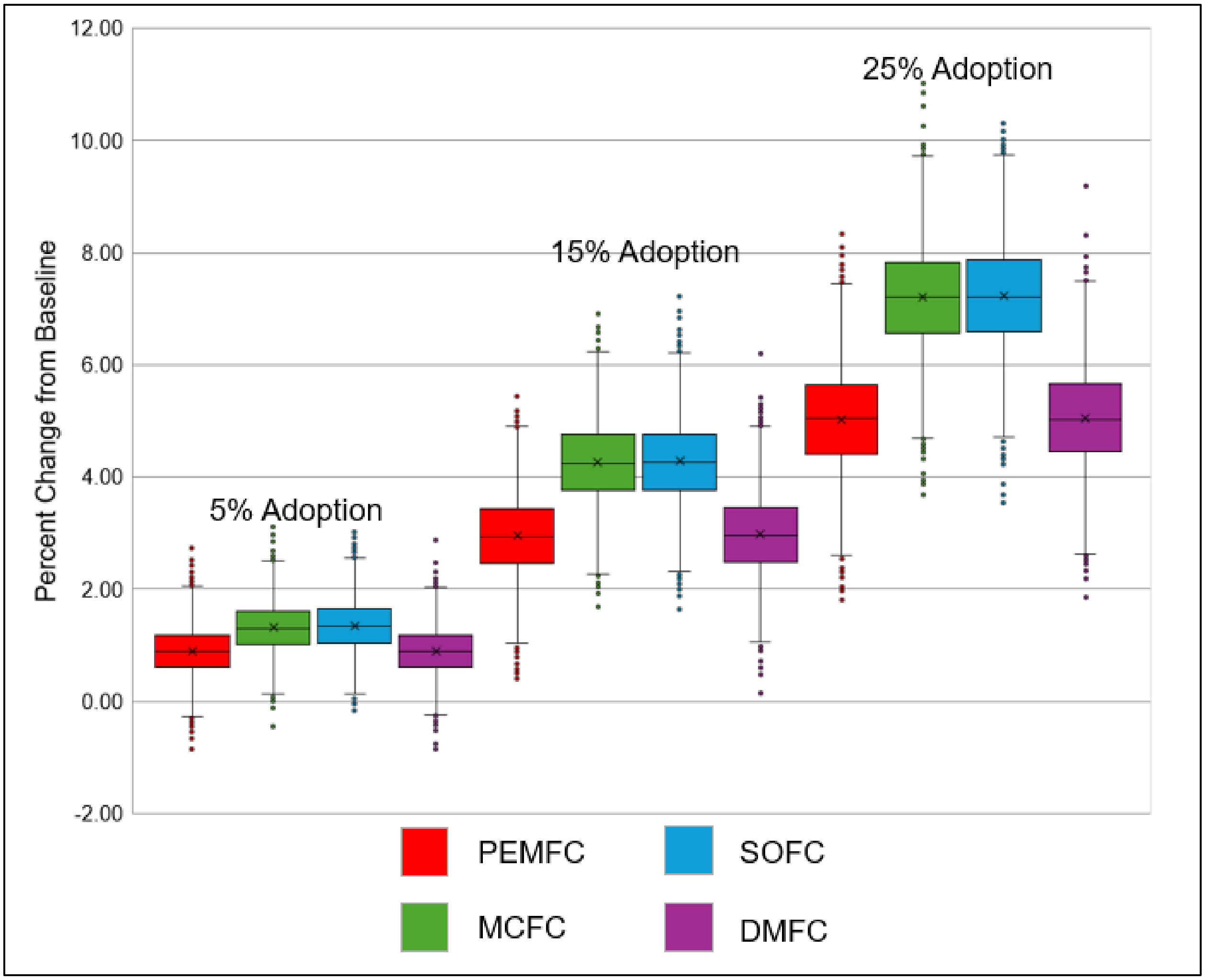


Figure 5-2. Change in total emissions under 5, 15, and 25% FC adoption scenarios

5.4.2 Impacts by sector and service type

The effort to reduce emissions from SSS might be most effective by focusing on certain types of ships. The following results explore the differences in fuel impacts on the sectors and services identified in Chapter 3. Table 5-9 shows the results by sector (Cargo, Tanker, and Support). Table 5-10 shows the results by service (Charter, Liner, Hub-and-Spoke, and Dedicated).

Cargo and tanker vessels are roughly equivalent in the scale of emissions reduction, exhibiting similar percent savings regardless of adoption rate and technology. As cargo vessels account for roughly twice the emissions, the overall impact of converting cargo ships is greater. Support vessels exhibit higher percent reductions (1-2%) mainly based on the fact that the majority of pilot boats and tugs operate out of Danish, Norwegian, Swedish, and Dutch ports, which each have low emissions factors relative to other countries.

Table 5-9. Impacts of FC adoption on shipping sector emissions

FC Technology & Adoption Rate	Cargo Emissions (tons CO_2)	Emissions change from Baseline	Tanker Emissions (tons CO_2)	Emissions change from Baseline	Support Emissions (tons CO_2)	Emissions change from Baseline
PEMFC						
5% adoption	587,156	-7,467	272,727	-2,303	6,481	-119
10% adoption	578,716	-15,907	268,279	-6,751	6,333	-267
15% adoption	568,333	-26,290	262,890	-12,140	6,166	-434
20% adoption	555,667	-38,956	256,824	-18,206	5,984	-616
25% adoption	540,722	-53,901	249,584	-25,446	5,791	-809
MCFC						
5% adoption	584,707	-9,916	271,424	-3,606	6,472	-128
10% adoption	573,569	-21,054	265,601	-9,429	6,311	-289
15% adoption	560,560	-34,063	258,936	-16,094	6,128	-472
20% adoption	545,102	-49,521	251,483	-23,547	5,940	-660
25% adoption	528,474	-66,149	243,384	-31,646	5,743	-857
SOFC						
5% adoption	584,678	-9,945	271,440	-3,590	6,469	-131
10% adoption	573,586	-21,037	265,586	-9,444	6,303	-297
15% adoption	560,532	-34,091	259,141	-15,889	6,131	-469
20% adoption	545,455	-49,168	251,721	-23,309	5,942	-658
25% adoption	528,703	-65,920	243,650	-31,380	5,730	-870
DMFC						
5% adoption	587,073	-7,550	272,775	-2,255	6,482	-118
10% adoption	578,457	-16,166	268,274	-6,756	6,331	-269
15% adoption	568,126	-26,497	263,045	-11,985	6,171	-429
20% adoption	555,228	-39,395	257,047	-17,983	5,992	-608
25% adoption	541,117	-53,506	250,337	-24,693	5,797	-803

Similar patterns arise when considering emissions changes by service. Charter vessels make up most of the sample fleet. The total emissions reductions are greatest from this service. In terms of emissions reduction percentage, liner services offer the highest potential by 1.5-2.0 percentage points compared to Charter and Hub-and-Spoke services.

Table 5-10. Impacts of FC adoption on shipping services

FC Technology & Adoption Rate	Charter Emissions (tons CO_2)	Emissions change from Baseline	Liner Emissions (tons CO_2)	Emissions change from Baseline	Hub-and-Spoke Emissions (tons CO_2)	Emissions change from Baseline	Dedicated Emissions (tons CO_2)	Emissions change from Baseline
PEMFC								
5% adoption	459,610	-3,179	183,480	-2,904	221,197	-3,315	2,189	-15
10% adoption	454,332	-8,457	179,884	-6,500	217,024	-7,488	2,162	-42
15% adoption	447,306	-15,483	175,791	-10,593	212,355	-12,157	2,125	-79
20% adoption	438,471	-24,318	171,140	-15,244	206,861	-17,651	2,083	-121
25% adoption	427,527	-35,262	166,057	-20,327	200,627	-23,885	2,027	-177
MCFC								
5% adoption	457,119	-5,670	182,908	-3,476	220,550	-3,962	2,186	-18
10% adoption	449,145	-13,644	178,626	-7,758	215,623	-8,889	2,155	-49
15% adoption	439,561	-23,228	173,830	-12,554	210,196	-14,316	2,108	-96
20% adoption	428,208	-34,581	168,605	-17,779	203,948	-20,564	2,062	-142
25% adoption	415,314	-47,475	162,938	-23,446	197,276	-27,236	2,010	-194
SOFC								
5% adoption	457,100	-5,689	182,916	-3,468	220,439	-4,073	2,186	-18
10% adoption	449,033	-13,756	178,700	-7,684	215,576	-8,936	2,155	-49
15% adoption	439,823	-22,966	173,970	-12,414	210,213	-14,299	2,111	-93
20% adoption	428,337	-34,452	168,804	-17,580	204,019	-20,493	2,064	-140
25% adoption	415,690	-47,099	163,157	-23,227	197,347	-27,165	2,013	-191
DMFC								
5% adoption	459,575	-3,214	183,572	-2,812	221,129	-3,383	2,188	-16
10% adoption	454,134	-8,655	179,788	-6,596	216,970	-7,542	2,163	-41
15% adoption	447,243	-15,546	175,779	-10,605	212,239	-12,273	2,124	-80
20% adoption	438,431	-24,358	171,160	-15,224	206,758	-17,754	2,080	-124
25% adoption	428,206	-34,583	166,141	-20,243	200,823	-23,689	2,034	-170

5.4.3 Impacts to Emission Intensity Metrics

The following results reflect changes to the emissions intensity metric: emissions per ton-mile. Reductions are shown across the board when comparing median values of the baseline model results and FC scenarios.

Table 5-11. Changes to emissions intensity metrics with FC adoption

HMFCA Scenario	Emissions (kg) per mil ton-nm	Percent change from Baseline
Baseline	**20.41**	**-**
PEMFC		
5% adoption	19.86	-0.55
10% adoption	19.41	-1.01
15% adoption	18.99	-1.43
20% adoption	18.51	-1.91
25% adoption	18.00	-2.41
MCFC		
5% adoption	19.71	-0.70
10% adoption	19.26	-1.15
15% adoption	18.61	-1.81
20% adoption	18.05	-2.36
25% adoption	17.52	-2.89
SOFC		
5% adoption	19.75	-0.66
10% adoption	19.21	-1.20
15% adoption	18.73	-1.68
20% adoption	18.11	-2.30
25% adoption	17.57	-2.85
DMFC		
5% adoption	19.90	-0.51
10% adoption	19.47	-0.94
15% adoption	19.04	-1.37
20% adoption	18.47	-1.94
25% adoption	17.87	-2.54

5.5 Discussion

The results of the study show that emissions from SSS can be reduced by introducing a substantial number of hydrogen fuel cell propelled ships. Baltic Sea shipping emissions have been reduced since the introduction of the Emissions Control Area (71). However, these reductions have not occurred to the degree required by the Paris Accords or at a rate that will meet newer IMO goals. Emissions from hydrogen production are higher in places where electricity is generated by fossil fuel power plants.

The underlying work for this research is (40). The authors described a wide range of emissions results from hydrogen fuel cells driven mainly by feedstocks. Since the publication of that work hydrogen production has increased in scale and become more efficient, but electric grids have not become cleaner in every country. For that reason there are still wide variations in potential emission changes between countries.

These results are not generalizable to other geographic areas, but the underlying parameters are. Emission factors can be calculated for additional countries if import/export data and electricity mix are easily established. Modeling a different set of ships only requires new or archived AIS trace data. The information is standardized enough across the globe to reproduce the data cleaning achieved in this work.

5.6 Conclusions

The Hydrogen Modified Fuel Cycle Emissions Model shows that each of the four fuel cell technologies can lead to emissions reductions in Baltic-North Sea region short sea shipping. These results are inclusive of all potential feedstocks for each FC technology reactant. As adoption rate of fuel cell technology increases, so do the emissions savings. The results of this chapter show, however, in the current fuel environment hydrogen is not a “zero-emission” option. A more targeted approach to emissions estimates is required to understand where the benefits of hydrogen conversion can be best utilized. For that reason, a targeted approach is applied in the next chapter.

The work in this chapter reflects a new application for Fuel Cycle Analysis models. These models have not been used previously to estimate either short-sea specific vessels or entire fleets. This work allows for both and is adaptable to other geographic regions or marine sectors.

Chapter 6: Identifying the ports and shipping routes best suited to hydrogen adoption.

6.1 Abstract

The preliminary model in Chapter 5 identifies that emissions are reduced to a great extent for certain vessel types – tankers are larger and tend to be closer to deadweight ton capacity more frequently than other vessel types. Reducing emissions is a global issue, but local stakeholders must act. The IMO has left technology development and deployment in the hands of individual member states and shippers. These stakeholders need to make cost-effective decisions when implementing or testing technology. Determining the vessels and routes that will result in the lowest emissions after converting a ship to hydrogen is therefore valuable information. Lowest investment cost and emissions, however, are not the only benefits that these stakeholders can produce. In this research I will identify the vessels and ports "best" suited to shift towards hydrogen power. This requires both quantitative and qualitative analysis to produce recommendations.

6.2 Introduction

Chapter 3 outlines the fact that not all shipping is created equally. 37% of vessels transport freight between the same ports regularly, but the remaining 63% of vessels are not involved in regularly scheduled voyages. Vessels that travel in a scheduled service might have greater opportunity to reduce or eliminate propulsion emissions if those scheduled sailings depart from ports with low emission factors, have available H_2 or methanol feedstocks, and can accommodate bunkering of new fuels.

Where, then, should infrastructure investment be focused? Are scheduled sailings regular enough or at such a scale to warrant the investment costs at these ports, or should investments focus more on heavily trafficked ports, regardless of vessel destination? This chapter covers the development of a framework for government bodies and the stakeholders in SSS to choose where best to invest in hydrogen fuel cell technology – both onboard ships and on shore for fuel storage and generation. It uses a mixed methodology to create this framework with both qualitative and quantitative measures.

First, the qualitative. Using the HMFCA model, changes in emissions are calculated for each port pairing or scheduled sailing. The modeling results are driven by two factors: vessel traffic and port-specific emissions factors fuel cell reactants. This chapter will compare the magnitude change between high-volume or high-traffic ports and low-emission factor ports.

Second, qualitative influencing factors are determined from the literature that cover characteristics of the subject ports and surrounding areas to determine whether or not hydrogen would be a good investment at that location or for the ships sailing into and out of that port. Key to this literature review is exploring factors that influenced decision-making during other energy-based shifts in the recent past. Namely, what drove decision making on solar and wind energy develop, the use of natural gas for various power requirements, and even the advent of nuclear energy for commercial use. This literature determines a set of criteria that regions should meet to support a transition to hydrogen energy for maritime operations.

6.3 Methodology

6.3.1 Port-specific emissions

In this chapter the HMFCA model was again used, this time for specific ports and port pairings. Parameters from Chapter 5 remain the same, considering low (5%) to high (25%) adoption, this time for specific ports. Since there are over 550 ports and 10,000 unique combination of ports observed, not every pairing is selected for this phase. The impact from fuel cell conversion is evaluated considering two factors: 1) highest impact based on vessel traffic volume and 2) highest impact based on potential emissions reduction. These factors are also broken down by port and by port origin-destination pairings. Ultimately each of the categories listed below were evaluated.

- Top 20 ports ranked by inbound and outbound vessel traffic.
- Top 20 port O-D pairings ranked by vessel traffic.
- Top 20 ports ranked by potential emissions reductions (Median FC_{EF} – Median MDO_{EF})
- Top 20 port O-D pairings ranked by potential emissions reduction (using combined emissions factors between both ports)

Emissions were calculated for full voyage transportation. It is not realistic to expect ships to use H_2 only between two ports in a voyage that may last 30 days and visit 6-7 ports of call. Two additional criteria exist for emissions reduction potential: a) the port demand must be greater than 10 ships per month, and b) a maximum of 4 ports are selected per country. The first criterion exists because the same adoption rates (5-25%) are applied as in Chapter 5. The second criterion was applied because two countries (Sweden and Norway) have particularly low potential H_2 rates. As a regional evaluation the analysis should not be limited to two states. Finally, the O-D pairings ranked by potential emissions reduction had to include at least one liner service to guarantee fueling would occur at that port location. Tables 6-1 and 6-2 shows the ports and port pairings.

The top 5% in each category (single port by traffic volume, origin-destination pair or liner service by traffic volume, single port by change in emissions, and origin-destination pair or liner service by change in emissions) were selected for analysis.

- Top 5% of ports by overall traffic
- Top 5% O-D pairs + other ports in liner + hub-and-spoke routes
- Compare Liner to Charter to Dedicated to Hub-and-spoke services
- Top 5%

6.3.2 Quantitative approach

Chapter 5 uses random sampling to generate the results. In this chapter we will thoughtfully analyze O-D pairings to determine the extent to which emissions can be reduced based on the fleets servicing those fleets. Emissions from the combustion side of the fuel cycle model are largely based on distance traveled and deadweight tonnage. The make-up of ship operating between O-D pairs and the distance between those pairs can vary widely. For that reason, emissions intensity should be considered: CO_2 per nautical mile or ton-nm

Table 6-1. Ports and port pairings selected for analysis based on total vessel traffic volume

Rank	Port	Vessel Traffic	Port O-D Pair (independent of direction)	Vessel Traffic
1	Rotterdam, NL	536	Rotterdam, NL - Hamburg, DE	85
2	Hamburg, DE	391	Hamburg, DE - Antwerp, BE	79
3	Gothenburg, SE	363	Gothenburg, SE - Skagen, DK	64
4	Antwerp, BE	333	Hamburg, DE - Bremerhaven, DE	52
5	Bremerhaven, DE	241	Rotterdam, NL - Antwerp, BE	39
6	Skagen, DK	229	Antwerp, BE - Bremerhaven, DE	36
7	Gdansk, PL	216	Rotterdam, NL - Bremerhaven, DE	33
8	Rostock, DE	184	Ust-Luga, RU - Turkey (all dest.)	29
9	Amsterdam, NL	152	Rotterdam, NL - Gothenburg, SE	28
10	Klaipeda, LT	140	Esbjerg, DK - Offshore Locations	27
11	Szczecin, PL	130	Bremerhaven, DE - Gdansk, PL	26
12	France (all dest)	127	Brofjorden, SE - Gothenburg, SE	25
13	Gydnia, PL	125	Rotterdam, NL - Gdansk, PL	24
14	Kiel, DEf	117	Gothenburg, SE - Copenhagen, DK	24
15	Aarhus, DK	109	Zeebrugge, BE - Bremerhaven, DE	21
16	Esbjerg, DK	108	Great Yarmouth, GB - Offshore Locations	20
17	Immingham, GB	88	Gdynia, PL - Klaipeda, Lithuania	20
18	Riga, LV	84	Rotterdam, NL - Teesport, GB	20
19	Mongstad, NO	78	Skagen, DK - Tallinn, EE	19
20	Helsingborg, SE	71	Aberdeen, GB - Offshore Locations	19

Table 6-2. Ports and port pairings selected for analysis based on emissions reduction potential

Port	Vessel Traffic	Emissions Reduction potential (g CO_2/MJ)	Port O-D Pair	Vessel Traffic	Combined Emission Factor (g CO_2/MJ)
Solvesborg, SE (SESOL)	22	-77.785	Tanager, NO (NOTAE)- Offshore Locations	17	9.680
Ystad, SE (SEYST)	29	-77.784	Gothenburg, SE < > Stenungsund, SE (SESTE)	16	12.135
Lidkoping, SE (SELDK)	10	-77.763	Gothenburg, SE < > Brofjorden, SE (SEBRO)	25	12.137
Karlshamn, SE (SEKAN)	36	-77.762	Gothenburg, SE < > Halmstad, SE (SEHAD)	11	12.211
Oslo, NO (NOOSL)	59	-75.527	Gothenburg, SE < > Helsingborg, SE (SEHEL)	10	12.265
Drammen, NO (NODRM)	35	-75.467	Mongstad, NO (NOMON) < > Gothenburg, SE	14	15.675
Moss, NO (NOMSS)	17	-75.458	Esbjerg, DK < > Offshore Locations (DK and NO)	38	17.365
Fredrikstad, NO (NOFRK)	46	-75.447	Skagen, DK < > Offshore Locations (DK and NO)	10	17.406
Tornio, FI (FITOR)	25	-64.129	Aarhus, DK < > Gothenburg, SE	14	23.399
Kokkola, FI (FIKOK)	10	-63.981	Skagen, DK < > Gothenburg, SE	64	23.478
Rauma, FI (FIRAU)	22	-63.667	Great Yarmouth, GB < > Offshore Locations	20	28.722
Uusikaupunki, FI (FIUKI)	12	-63.641	Aarhus, DK < > Fredericia, DK (DKFRC)	15	34.671
France (all destinations)	127	-59.816	Antwerp, BE < > Gothenburg, SE	16	35.375
Riga, LV (LVRIX)	75	-56.905	Den Helder, NL (NLDHR) < > Offshore Locations	14	37.326
Ventspils, LV (LVVNT)	30	-56.659	Antwerp, BE < > Mongstad, NO (NOMON)	12	38.907
Frederikshavn, DK (DKFDH)	50	-56.488	Amsterdam, NL < > Gothenburg, SE	10	43.356
Hirtshals, DK (DKHIR)	26	-56.456	Rotterdam, NL < > Gothenburg, SE	28	43.369
Skagen, DK (DKSKA)	229	-56.454	Antwerp, BE < > France (all destinations)	10	46.193
Aalborg, DK (DKAAL)	78	-56.448	Rotterdam, NL < > Oslo, NO	14	46.848
Klaipeda, LT (LTKLJ)	140	-51.043	Rotterdam, NL < > Mongstad, NO	17	46.900

6.3.3 Qualitative approach

Through literature review of other major energy shifts, factors that can influence the decision to invest in marine hydrogen fuel cell technology are identified. These factors, which are detailed in the discussion section, were assessed for each of the identified port or O-D pair or liner service in the reduced dataset. Some factors can be quantified such as the presence of ferry services and existing bunker sites, but most are evaluated as having either potential to support or not support a greater hydrogen economy that lends itself marine hydrogen investment.

6.3.4 Generate influencing factor data for O-D port pairs from Modified Fuel Cycle Emissions Model.

Chapter 5 randomly assigns hydrogen technology to vessel trajectories. To compare each O-D port pair, the model must be run across all ships traveling between each port pairing. Deciding to invest in marine hydrogen is a major decision that has political and technological ramifications if attempted to do so at scale. The investment required could be equivalent to the start-up of the solar and wind energy sectors in the U.S. and Europe. To ultimately make recommendations based on this research, additional literature review and qualitative research will be conducted to understand what conditions influenced those sectors in the early days across different markets.

6.4 Results

6.4.1 FC Impacts at high-traffic Baltic-North Sea region port emissions

Heavy traffic into and out of a port does not automatically result in emissions reduction. At low adoption (5%) of fuel cell technology 7 of the 20 identified ports experienced net increases in emissions. All of these ports are located either in Germany or Poland. German electricity emissions are borderline competitive with fossil fuel marine power plants. However when the diverse set of feedstocks are accounted for the median emissions rate for a fuel cell ship refueling and departing a German port is higher than the median rate for an MDO-fueled vessel. Poland is still so reliant on coal-fired power plants that is unlikely domestically produced hydrogen and methanol can achieve low fuel cycle emission rates.

6.4.2 FC Impacts at high-traffic Baltic-North Sea region ports pairing emissions

The top 20 SSS routes (independent of direction) based on vessel traffic are shown in Table 6-4. The simulation results capture the wide range of emissions factors influencing emissions on these routes. In most cases fuel cell adoption would result in emissions reductions, but not for routes involving Russia, Turkey, and Poland. These countries are too reliant on fossil fuels for electricity production to see benefits from fuel cell adoption. The Hamburg-Bremerhaven route emissions increase is not anomalous. Germany has a relatively high emissions rate due to the reliance on fossil fuels for half of its electricity production. This is one of few Germany-to-Germany routes with heavy traffic and as such does not benefit from lower corresponding rates in the port pairing.

Table 6-3. Changes to emissions by port

Rank	Port	Vessel Traffic	Baseline Emissions (BL)	Minimum FC Emissions (FC_{min})	Maximum FC Emissions (FC_{max})	% Reduction from Baseline (FC_{max} - BL, FC_{min} - BL)
1	Rotterdam, NL	536	47,411	44,718	47,165	0.52 - 5.68
2	Hamburg, DE	391	37,922	36,017	38,050	-0.34 - 5.02
3	Gothenburg, SE	363	48,234	38,139	46,478	3.64 - 20.93
4	Antwerp, BE	333	42,596	38,613	42,289	0.72 - 9.35
5	Bremerhaven, DE	241	28,826	27,491	28,894	-0.24 - 4.63
6	Skagen, DK	229	29,936	25,572	29,309	2.1 - 14.58
7	Gdansk, PL	216	34,236	32,680	34,792	-1.63 - 4.54
8	Rostock, DE	184	16,490	15,750	16,519	-0.18 - 4.48
9	Amsterdam, NL	152	8,557	8,090	8,526	0.37 - 5.47
10	Klaipeda, LT	140	25,800	22,486	25,298	1.95 - 12.85
11	Szczecin, PL	130	5,849	5,587	5,949	-1.71 - 4.47
12	France (all dest.)	127	11,432	9,813	11,352	0.7 - 14.17
13	Gdynia, PL	125	20,972	20,065	21,250	-1.32 - 4.33
14	Kiel, DE	117	7,958	7,700	7,975	-0.21 - 3.25
15	Aarhus, DK	109	5,948	5,134	5,824	2.09 - 13.69
16	Esbjerg, DK	108	6,701	5,820	6,577	1.85 - 13.15
17	Immingham, GB	88	8,922	8,112	8,849	0.82 - 9.08
18	Riga, LV	84	6,790	5,682	6,656	1.98 - 16.33
19	Mongstad, NO	78	19,651	15,865	19,291	1.83 - 19.27
20	Helsingborg, SE	71	4,380	3,503	4,251	2.95 - 20.03

Table 6-4. Changes to emissions by port O-D pairs

Rank	Port O-D Pair (ind. of direction)	Vessel Traffic	Baseline Emissions (BL)	Minimum FC Emissions (FC_{min})	Maximum FC Emissions (FC_{max})	% Reduction from Baseline (FC_{max} - BL, FC_{min} - BL)
1	Rotterdam, NL - Hamburg, DE	85	12,618	11,961	12,604	0.11 - 5.21
2	Hamburg, DE - Antwerp, BE	79	12,506	11,691	12,487	0.15 - 6.51
3	Gothenburg, SE - Skagen, DK	64	2,389	1,975	2,343	1.94 - 17.31
4	Hamburg, DE - Bremerhaven, DE	52	3,701	3,535	3,705	-0.11 - 4.48
5	Rotterdam, NL - Antwerp, BE	39	1,136	1,055	1,133	0.2 - 7.06
6	Antwerp, BE - Bremerhaven, DE	36	4,800	4,487	4,795	0.11 - 6.52
7	Rotterdam, NL - Bremerhaven, DE	33	4,507	4,292	4,506	0.01 - 4.77
8	Ust-Luga, RU - Turkey (all dest.)	29	17,072	16,294	17,221	-0.87 - 4.56
9	Rotterdam, NL - Gothenburg, SE	28	4,418	3,946	4,395	0.51 - 10.68
10	Esbjerg, DK - Offshore Locations	27	913	786	907	0.68 - 13.9
11	Bremerhaven, DE - Gdansk, PL	26	19,752	19,026	19,815	-0.32 - 3.67
12	Brofjorden, SE - Gothenburg, SE	25	756	680	748	1.06 - 10.02
13	Rotterdam, NL - Gdansk, PL	24	6,384	6,128	6,382	0.02 - 4.01
14	Gothenburg, SE - Copenhagen, DK	24	733	612	722	1.61 - 16.52
15	Zeebrugge, BE - Bremerhaven, DE	21	1,425	1,339	1,425	0.02 - 6.03
16	Gt Yarmouth, GB - Offshore-GB	20	79	72	79	0.37 - 8.36
17	Gdynia, PL - Klaipeda, LT	20	585	519	582	0.5 - 11.24
18	Rotterdam, NL - Teesport, GB	20	597	563	596	0.08 - 5.66
19	Skagen, DK - Tallinn, EE	19	5,604	4,990	5,591	0.23 - 10.97
20	Randers, DK - Copenhagen, DK	19	290	247	288	0.5 - 14.53

6.4.3 FC Impacts at low emission Baltic-North Sea region ports

Table 6-5 shows the potential emissions reductions from all ships travelling to and from the ports with the lowest median FC emission factors. These calculations are inclusive of each ship's full voyage, not simply the sub-voyages involving the listed ports. As expected, the ports with the lowest median emission factors almost universally result in emissions reductions. The sole exception to this is Ystad. At 5% adoption rate there is an *increase* in emissions. This can be directly attributed to Ro-Ro routes between Ystad and ports in Poland. These ships have high power-output, travel at high speed, and have low capacity utilization, resulting in high emissions per ton-nm. Poland's emission factors are high enough to offset any savings producing hydrogen in Sweden can offer.

Table 6-5. Changes to emissions at low FC EF ports

Rank	Port	Vessel Traffic	Emissions Reduction potential (g/MJ)	Baseline Emissions (BL)	Minimum FC Emissions (FC_{min})	Maximum FC Emissions (FC_{max})	% Reduction from Baseline (FC_{max} - BL, FC_{min} - BL)
1	Solvesborg, SE	22	-77.785	370	363	295	1.76 - 20.04
2	Ystad, SE	29	-77.784	559	560	520	-0.31 - 6.86
3	Lidkoping, SE	10	-77.763	281	280	225	0.31 - 19.92
4	Karlshamn, SE	36	-77.762	2,014	1,980	1,689	1.68 - 16.16
5	Oslo, NO	59	-75.527	2,922	2,859	2,357	2.15 - 19.32
6	Drammen, NO	35	-75.467	1,205	1,174	974	2.6 - 19.19
7	Moss, NO	17	-75.458	510	507	415	0.58 - 18.68
8	Fredrikstad, NO	46	-75.447	2,074	2,045	1,741	1.38 - 16.06
9	Tornio, FI	25	-64.129	2,252	2,210	1,862	1.87 - 17.32
10	Kokkola, FI	10	-63.981	1,208	1,201	1,038	0.57 - 14.11
11	Rauma, FI	22	-63.667	2,102	2,074	1,746	1.32 - 16.93
12	Uusikaupunki, FI	12	-63.641	822	816	713	0.7 - 13.23
13	France (all dest)	127	-59.816	11,432	11,352	9,813	0.7 - 14.17
14	Riga, LV	75	-56.905	6,790	6,656	5,682	1.98 - 16.33
15	Ventspils, LV	30	-56.659	2,655	2,612	2,243	1.65 - 15.53
16	Frederikshavn, DK	50	-56.488	954	942	852	1.25 - 10.68
17	Hirtshals, DK	26	-56.456	329	327	295	0.76 - 10.55
18	Skagen, DK	229	-56.454	29,936	29,309	25,572	2.1 - 14.58
19	Aalborg, DK	78	-56.448	1,835	1,799	1,568	1.97 - 14.55
20	Klaipeda, LT	140	-51.043	25,800	25,298	22,486	1.95 - 12.85

6.4.4 FC Impacts at low emission Baltic-North Sea region ports

The potential for emissions reductions when ships convert from fossil fuel powerplants to hydrogen fuel cells is not limited to the raw emissions factor calculation. As Table 6-6 below shows, the change from baseline emissions is maximized when vessel traffic is high. What is not shown are ship types and sized. The Skagen < > Gothenburg route is dominated by large crude oil tankers and other heavily laden bulk freighters and chemical/oil tankers. The Mongstad < > Gothenburg route is likewise characterized by large, heavily laden ships.

Table 6-6. Changes to emissions at low FC EF ports

Rank	Port O-D Pair	Vessel Traffic	Combined Emission Factor (g/MJ)	Baseline Emissions (BL)	Minimum FC Emissions (FC_{min})	Maximum FC Emissions (FC_{max})	% Reduction from Baseline (FC_{max} - BL, FC_{min} - BL)
1	Tanager, NO - Offshore-NO	17	9.680	306	269	305	0.5 - 12.15
2	Gothenburg, SE - Stenungsund, SE	16	12.135	92	75	93	-0.38 - 19.17
3	Gothenburg, SE - Brofjorden, SE	25	12.137	756	680	748	1.06 - 10.02
4	Gothenburg, SE - Halmstad, SE	11	12.211	171	137	170	0.36 - 19.54
5	Gothenburg, SE - Helsingborg, SE	10	12.265	613	520	610	0.52 - 15.11
6	Mongstad, NO - Gothenburg, SE	14	15.675	1,311	1,056	1,317	-0.53 - 19.43
7	Esbjerg, DK – Offshore-DK/NO	38	17.365	1,362	1,167	1,352	0.7 - 14.28
8	Aarhus, DK - Gothenburg, SE	14	23.399	1,069	911	1,062	0.6 - 14.73
9	Skagen, DK - Gothenburg, SE	64	23.478	2,389	1,975	2,343	1.94 - 17.31
10	Gt Yarmouth, GB - Offshore-GB	20	28.722	79	72	79	0.37 - 8.36
11	Aarhus, DK - Fredericia, DK	15	34.671	506	439	504	0.55 - 13.29
12	Antwerp, BE - Gothenburg, SE	16	35.375	2,668	2,350	2,655	0.5 - 11.93
13	Den Helder, NL - Offshore-NL	14	37.326	137	132	137	0.04 - 3.93
14	Antwerp, BE - Mongstad, NO	12	38.907	849	727	863	-1.59 - 14.37
15	Amsterdam, NL - Gothenburg, SE	10	43.356	1,232	1,056	1,230	0.21 - 14.33
16	Rotterdam, NL - Gothenburg, SE	28	43.369	4,418	3,946	4,395	0.51 - 10.68
17	Antwerp, BE - France (all dest)	10	46.193	460	414.12	458	0.37 - 10.08
18	Rotterdam, NL - Oslo, NO	14	46.848	2,713	2,535.93	2,709	0.16 - 6.54
19	Rotterdam, NL - Mongstad, NO	17	46.900	2,972	2,630.40	2,962	0.33 - 11.5
20	Rotterdam, NL - Tanager, NO	10	46.977	927	813.21	925	0.19 - 12.32

6.4.5 Influencing Factors and High-Traffic or Low-Emission Ports

The quantitative analysis in this chapter utilizes the HMFCA model for hydrogen systems on port pairings (single origin and single destination) and common port pathways (routine visits between more than two ports). "Best" suit for H_2 adoption cannot be measured by SSS freight-based emissions alone. This work developed a series of influencing factors that can contribute to the development of a hydrogen economy. The factors are described below with commentary about which ports benefit from each. Full results from researching the individual ports are included in Table 6-7 located after the description of each influencing factor.

IF1: Ferry Activity (FA)
The presence of local and regional passenger ferry services can aid in the development of a hydrogen economy. Ferries operate routinely between the same ports and all fueling infrastructure needs to be local. Ferry administrators can share in the cost of new infrastructure or receive governmental aid unavailable to the private sector. This influencing factor omits large international ferries used to move trucks between countries. These vessels were included as SSS vessels in the HMFCA model. Ports with municipally operated water taxi services were included as those with ferry activity.

Fuel cell technology has been demonstrated in ferry networks. The MF Hydra has been operated by Norled since 2023. Additional hydrogen ferry builds have been contracted by the agency as well. Many major Norwegian, Sweden, and Danish ports have existing ferry routes to local and regional destinations. The major shipping hubs of Hamburg, Gothenburg, and Rostock also have local ferry services supporting passenger transportation. In all 23 of the 36 unique ports identified as having high traffic or low emission factors have ferry services.

IF2: Bunkering Facilities (B)
The presence of existing fuel storage (bunkering) facilities is a requirement for a hydrogen economy. Any natural gas or liquid fuel infrastructure that can be reused or converted to hydrogen and methanol depots would reduce the required investment cost for a new maritime energy source. Since hydrogen is not volumetrically energy dense large volumes often need to be cryogenically stored to reduce the footprint of tanks. Experience with LNG and other gaseous fuels is a positive addition to simply having bunkering facilities.

It should be noted that ships can refuel at almost every port within this study's dataset, but that does mean each port has bunkering facilities. At smaller and remote ports refueling is a chartered service. Fuel may be shipped to the port by truck or by sea on a barge or bunkering tanker. 29 of the 35 selected ports have bunkering facilities, about half (15) of which include LNG terminals and bunkering. France was excluded from this analysis as the "port" is an aggregate location for all French ports involved in Baltic-North Sea SSS.

IF3a-c: Feedstock Availability (FS)
As explained in Chapter 5 there are many feedstock materials for H_2 and methanol. Each port was evaluated based on the availability of these feedstocks locally, noting that transportation was almost always required to some degree. This Influencing Factor was considered for water hydrolysis (IF3a), natural gas (IF3b), and biomass availability (IF3c). Whether a port has an active hydrolysis plant or has plans to build one in the future determines the designation: Yes, this factor can influence the local hydrogen economy or no, this factor does not have local influence. Ownership of these facilities does not need to be tied to port authorities, terminal operators, or bunkering firms. Existence and location were the only parameters. Build out of

electrolysis facilities has progressed rapidly in the region over the last few years. 21 of 36 ports have existing or planned facilities nearby.

The natural gas influencing factor (IF3b) is tied mainly to the source of natural gas. As described in Chapter 4, fuels are imported to Baltic-North Sea region countries from trading partners throughout the world. If a high share (75%+) of natural gas is imported to a country (or self-produced) are from regional sources (e.g., Denmark, Norway, and the United Kingdom) then natural gas is a relatively low emission feedstock for H_2 and methanol, or can be directly fed through molten carbonate and solid oxide fuel cells. 24 of sample 36 ports had access to this lightly transported natural gas.

Finally, the biomass Influencing Factor (IF3c) is also related to national availability of biomass feedstocks. Countries like Finland and Sweden have established timber, pulp paper, and finished wood product industries. Indeed both countries are actively converting the waste products from these industries to biofuels. Other nations could rely heavily on waste from agriculture. The Netherlands and Estonia produce enough biomass to sustain the SSS industry's energy requirements at up to a 25% adoption rate. In the case of the Netherlands this does assume that destination ports are equally responsible for providing fuel. Of the selected ports only Immingham, UK and Antwerp, Belgium as unable to fill SSS energy needs from local biomass sources.

IF4a-b: Electric Grid Energy Mix (EN)

Low-carbon electricity production is a requirement for low-carbon hydrogen and methanol production. The current electricity grid production capacity mixes (IF4a) are analyzed to determine if a port benefits from local hydrogen production. Many regional countries already rely on wind, nuclear, and hydroelectric power for their electricity. Planned future mixed are also considered (IF4b). The Netherlands, Denmark, and Germany have all announced future wind farm plans, which reduce the national emissions factor for electricity production. Similar announcements are viewed as positive influencing factors, but they must also be weighed against current demand and capacity. A 50-MW wind farm has limited impact on a grid with 70 MW of fossil fuel-fire power plant capacity.

All Nordic countries plus France, Latvia, Lithuania, and the Netherlands rely on renewable energy or nuclear for the majority of electricity production. The emission rate per MJ of energy consumed is therefore lower than fossil fuel combustion and leads to reductions in maritime emissions if fuel cell reactants are produced in those nations.

Some Baltic-North Sea region countries have developed long-term electric grid generation plans and have announced future solar and wind projects. These include Germany, the Netherlands, and Poland. Incorporating these future energy mixes would influence the results of Chapter 6. Figure 6-1 shows additional potential emissions reduction (b) when considering planned energy mixes compared to the existing mixes in 2023 (a).

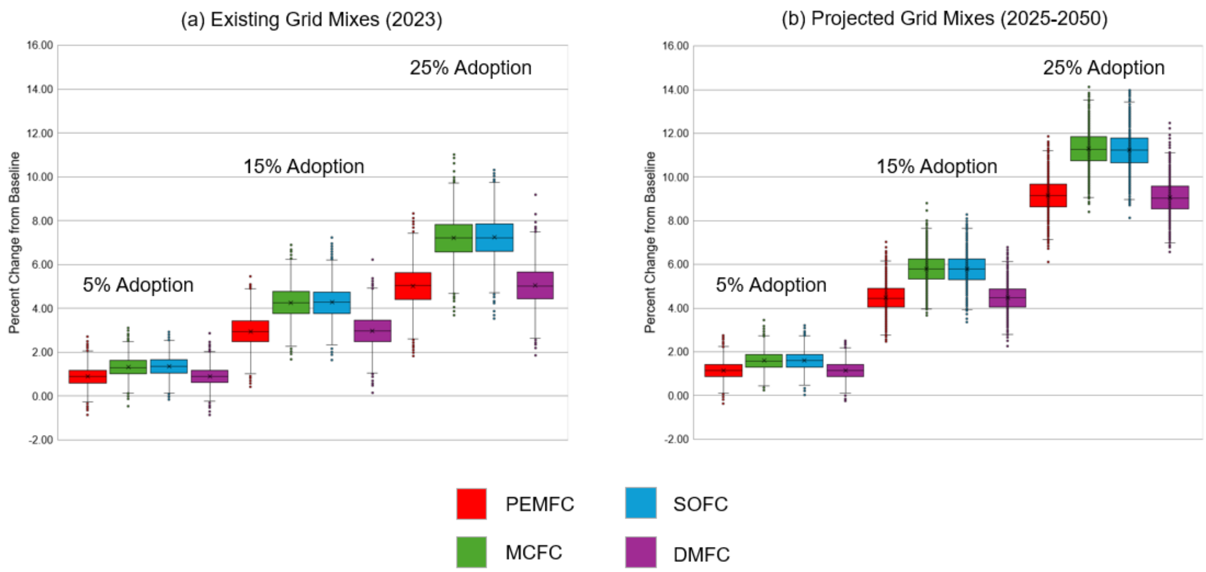


Figure 6-1. Change in emissions reduction due to increase in renewable electricity generation

IF5: Funding Availability ($)

This factor considers the availability of government loans, grants, and other financing programs that have been directed at hydrogen production or use in transportation. All countries except Latvia and Lithuania have directly invested in the hydrogen economy or received EU funding.

IF6: Lowest Capacity Usage (C)

Marine powerplants are designed based on maximum deadweight tonnage. Within the dataset used for this study it was noted that capacity is underutilized for almost all ship types. By identifying the ports with the lowest capacity usage, it can be suggested that fuel cell power plants can be designed for the observed capacity utilization rather than deadweight tonnage. There are risks to this strategy, but reducing the size of fuel cells would result in cost savings.

IF7: Shipbuilding and related industries (SB)

Many influencing factors identified have focused on the landside portion of a hydrogen economy. IF7 addresses the ships directly. Most shipbuilding has migrated to China, Japan, and South Korea. Powerplant production has likewise shifted to those countries as well as Indonesia and Vietnam. There are a few exceptions: the Netherlands still produces a significant number of mid-sized dry cargo vessels. The giants in powerplant production: Wartsila (Finland), MAN-B&W (Germany/Denmark), and Caterpillar (US) still have a presence in the region for various types of equipment as well as maintenance for ship power plants. The existence of these companies is viewed as a positive influence on hydrogen reliance provided the manufacturers become involved in R&D or manufacturing.

Table 6-7. Evaluation of High-Traffic and Low-Emission Ports across Influencing Factors

Rank	Port	Vessel Traffic	Ferry Activity	Bunkering Facilities	Feedstock Availability - Hydrolysis	Feedstock Availability - NG	Feedstock Availability - Biomass	Current Energy Mix	Future Energy Mix Projections	Funding Availability	Lowest Capacity Usage	Shipbuilding	Positive Factors
High-Traffic Ports													
1	Rotterdam, NL	536	-	✓	✓	✓	✓	- /✓	✓	✓	-	✓	7.5
2	Hamburg, DE	391	✓	✓	✓	-	✓	-	-	✓	-	-	5.0
3	Gothenburg, SE	363	✓	✓	-	✓	✓	✓	✓	✓	-	-	7.0
4	Antwerp, BE	333	-	✓	✓	✓	-	✓	✓	✓	-	-	6.0
5	Bremerhaven, DE	241	✓	✓	✓	-	✓	-	-	✓	-	-	5.0
6	Skagen, DK	229	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
7	Gdansk, PL	216	-	✓	-	✓	✓	-	-	✓	-	-	4.0
8	Rostock, DE	184	✓	✓	✓	-	✓	-	-	✓	✓	-	6.0
9	Amsterdam, NL	152	✓	-	-	✓	✓	- /✓	✓	✓	✓	✓	7.5
10	Klaipeda, LT	140	✓	✓	-	-	✓	-	-	-	✓	-	4.0
11	Szczecin, PL	130	-	✓	-	✓	✓	-	-	✓	-	-	4.0
12	France (all dest)	127	-	-/✓	✓	-	✓	✓	✓	✓	-	-	5.5
13	Gdynia, PL	125	-	✓	-	✓	✓	-	-	✓	-	-	4.0
14	Kiel, DE	117	✓	-	✓	-	✓	-	-	✓	-	-	4.0
15	Aarhus, DK	109	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
16	Esbjerg, DK	108	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	9.0
17	Immingham, GB	88	-	✓	-	✓	-	✓	✓	✓	-	-	5.0
18	Riga, LV	84	-	✓	-	-	✓	✓	✓	-	✓	-	5.0
19	Mongstad, NO	78	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	9.0
20	Helsingborg, SE	71	✓	✓	-	✓	✓	✓	✓	✓	✓	-	8.0
Low-Emission Ports													
1	Solvesborg, SE	22	✓	✓	-	✓	✓	✓	✓	✓	✓	-	7.0
2	Ystad, SE	29	✓	✓	-	✓	✓	✓	✓	✓	- /✓	-	7.5
3	Lidkoping, SE	10	-	-	✓	✓	✓	✓	✓	✓	✓	-	7.0
4	Karlshamn, SE	36	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	9.0
5	Oslo, NO	59	✓	✓	-	✓	✓	✓	✓	✓	-	-	7.0
6	Drammen, NO	35	-	✓	✓	✓	✓	✓	✓	✓	-	-	7.0
7	Moss, NO	17	✓	-	✓	✓	✓	✓	✓	✓	✓	-	8.0
8	Fredrikstad, NO	46	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	9.0
9	Tornio, FI	25	-	✓	✓	-	✓	✓	✓	✓	✓	-	7.0
10	Kokkola, FI	10	✓	-	✓	-	✓	✓	✓	✓	✓	- /✓	7.5
11	Rauma, FI	22	✓	-	-	-	✓	✓	✓	✓	✓	- /✓	6.5
12	Uusikaupunki, FI	12	-	✓	-	-	✓	✓	✓	✓	✓	-	6.0
13	France (all dest)	127	See high-traffic port entry above										
14	Riga, LV	75	See high-traffic port entry above										
15	Ventspils, LV	30	-	✓	-	-	✓	✓	✓	-	✓	-	5.0
16	Frederikshavn, DK	50	✓	✓	✓	✓	✓	✓	✓	✓	-	-	8.0
17	Hirtshals, DK	26	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	9.0
18	Skagen, DK	229	See high-traffic port entry above										
19	Aalborg, DK	78	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	9.0
20	Klaipeda, LT	140	See high-traffic port entry above										

The Influencing Factor matrix shows that the countries with the highest number of positive influences on the creation of a hydrogen economy are Denmark, Norway, and Sweden. With significant trade between these countries as well as the most extensive support fleets it makes sense to focus investments at key ports in these countries. Skagen, Aarhus, Esbjerg, Karlshamn, and Frederikstad could spur growth of the hydrogen industry by leveraging preexisting factors.

6.5 Discussion

Identifying "low hanging fruit" is important for two parties: governments with a vested interest in reducing emissions, and ship owners interested in reducing their direct emissions, but also gaining a competitive advantage in the marketplace. Maersk and Yara are two prime examples of the latter. IMO Resolution MEPC.377 has essentially placed the onus of determining emission reduction technologies and pathways on its member states and ship owners (7). Those parties have stated that it will take a variety of alternative fuels and vessel design changes to achieve the IMO goals. It is therefore vital to research sectors of the maritime industry to determine the feasibility of hydrogen fuel cells and other technologies. This research has segmented short sea shipping from ocean-going shipping and seeks to further subdivide SSS geographically in part to answer that feasibility question.

Major shifts in fuel reliance have occurred in the past. The emergence of solar and wind energy for electricity consumption are two such examples. In part, the transition to these energy sources was stimulated by state intervention in Scandinavia and the United States. It is likely similar interventions are required for maritime alternative fuels including hydrogen. But countries need to understand where to invest. There are dozens of commercial ports in the countries studied in this research. Should money be allocated to all bunkering ports, the ports with the lowest risk of failure, or the ports with the highest traffic. This chapter endeavors to answer questions similar to these.

The research and findings in this chapter as well as the previous chapters are geographically specific. The results, then, are not specifically generalizable. It cannot be assumed that because switching to hydrogen fuel cell ships in the Baltic would reduce SSS emissions, the same would be true for other regions. But this research is still instructive. The influencing factors identified in this chapter can inform policy and business decisions elsewhere. A small number of ports might be identified as feasible options for a hydrogen economy. This could mean countries with less port infrastructure than Nordic countries could still benefit from hydrogen. Conversely, if benefits are determined to be widespread, the window opens to hydrogen in a more geographically diverse set of ports globally. Finally, the results from the HMFCA do not apply to any other geographic region. However, the application of the HMFCA can be replicated for any fleet of SSS with modified inputs.

The projected political climate plays a role in industry efforts to decarbonize. While all IMO member states have agreed to Resolution MEPC.377, state support can waiver and change over time. As of 2026, the IMO is considering additional programs than will support decarbonization efforts including the Net-Zero Framework. This framework would include a pricing mechanism to charge shippers and carriers for noncompliance with a global fuel standard (98). Since adoption of Resolution MEPC.377 and the introduction of the Net-Zero Framework, the United States, an IMO member state, has become hostile to decarbonization plans. The administration has gone as far as to say penalties could be assessed against countries supporting the emissions penalty who trade with the United States (99). This is significant because ships involved in Baltic-North Sea short sea shipping are exclusively based in that region. 40% of vessels from this study’s SSS sample carry freight too and from ports outside Europe, including with the United States.

Chapter 7: Conclusions and Future Research

7.1 Summary

Ultimately, this dissertation details the estimated impacts of hydrogen fuel cell adoption on a specific case of short sea shipping. However, each chapter contributes to the wider body of work. In Chapter 3 a replicable process for identifying and analyzing short sea traffic using publicly available data is detailed. This process can be modified or scaled to focus on different sectors: fishing, passenger transport, inland waterway activity, or port operations. Chapter 4 establishes a previously unreported emissions estimate. This estimate and similar estimates using the same process are useful to an array of stakeholders: shippers, carriers, port authorities, and policy makers. Chapter 5 develops a model and process that can be adapted for technologies beyond hydrogen: dual-fuel systems, modular nuclear, battery electric, and beyond. Finally, Chapter 6 provides commentary on the approach stakeholders should take to prioritizing the major investments required for a major energy shift.

7.2 Limitations

Limitations to each stage of the model are described in each chapter. To summarize, those limitations are related to weather and sea conditions, ship design characteristics, fuel feedstock origins, and fueling data.

This MFCA model does not take weather and sea conditions into consideration. In adverse weather and heavy seas, the required power to move a ship at a certain speed increase from baseline. The hull efficiency parameter in the MFCA and HMFCA models does account for changes in sea conditions, but the efficiency losses compared to those form extrusions and hull geometry are not quantified.

Some ship design parameters are estimated rather than recorded based on real data. Information like power plant size, cargo capacity, auxiliary power systems, and propeller design are missing for many ships in the vessel source material. Propeller design was accounted for in the propeller efficiency parameter. Modern ships tend to have more efficient propeller designs, but the actual design is rarely listed. Auxiliary power systems are not included in the emissions calculations. Ships may have waste heat recovery systems that reduce energy demand or auxiliary systems to power crew quarters, but these are unknown for most ships. The model is therefore limited to propulsion systems only. Cargo capacity is known for the majority of ships, and those known capacities are used to estimate the capacities of other ships. Similarly, power plant size was estimated for omitted ships using the same process.

7.3 Areas for future work

The limitations of the models leave room for future research. There are also opportunities for expanding this work to other areas of maritime shipping. These areas would include incorporation of weather and sea conditions as parameters, including inland waterways, determinations of tug activities beyond movement, broadening the scope to include new geographic areas and maritime sectors, and developing scenario analysis strategies.

This model does not consider weather conditions in calculations. Heavy seas, adverse winds, and even temperature can impact how much power is required to move a ship at a given speed resulting in an underestimate of emissions in this model. There are existing models designed specifically to measure the impact of weather on emissions as well as sufficient historical data to include these factors in the MFCA and HMFCA model.

Deepsea and inland waterway vessels were specifically omitted from this analysis. Deepsea vessels often leave the study region and whole voyage information is unavailable. With voyage and destination information, though, the models can easily be applied to deep sea ships. Inland waterway vessels were excluded due to lack of ship design characteristics. While whole voyages can be seen in the AIS trace data, capacity, power output, and even sometimes ship dimensions are missing for these vessels on public databases. Researchers with industry knowledge could build this dataset or run the model on single ships.

Tugboats differ from most other support craft in this study in one respect: their power is used to moved larger, less easily maneuvered vessels. AIS trace data does not clearly identify when a tug is underway and assisting another ship vs. underway and simply guiding a ship from a distance. Additionally, it is unclear when tugs are involved in moving barges. This study may have underestimated tug emissions because power output is based on draft. A tug pushing or pulling another craft does not experience the same change in draft as one loaded vertically with cargo. A geographic clustering algorithm could be used to determine when a tug is actively assisting a ship by comparing parallel AIS trace paths that exhibit similar speeds.

Finally, the HMFCA model lends itself well to scenario analysis. Fuel feedstock, adoption rates, and grid emissions were all treated as parameters that be further specified. Comparisons can be made for different feedstock scenarios. An example is the use of “green” hydrogen versus. “blue” or “gray” hydrogen, or hydrogen produced from electrolysis with zero-emission energy sources versus hydrogen produced from fossil fuels (coal, natural gas, and petroleum). Another scenario would be measuring the impacts of load consolidation. This work showed that the average ship sailed with 20-30% of its cargo capacity unutilized. The data show that similar ships depart the same port within days, each with excess capacity. Consolidating loads across ships, while delaying deliveries, could reduce the fleet size and total emissions in the region.

The selection of “low-emission” ports is based entirely on the port-specific emissions factors. Another scenario could account for the emissions per ton-mile of the vessels traveling in and out of those ports. Ultimately, the largest or most heavily laden vessels contribute the highest rates of emissions. As Section 6.4.4 notes, the greatest reductions are observed when large, heavily laden ships are a large share of vessel traffic (e.g., Skagen-Gothenburg). Future analysis should include an approach targeted as vessels and vessel classes rather than solely ports.

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