SAFETY AND TRANSPORT
MARITIME

Marine vessel electrification and infrastructure challenges: Strömstad case study

Joanne Ellis
Nelly Forsman
Sara Kilicaslan

RISE/SSPA Report : RE41199324-01-00-A

Interreg
North Sea Region
ZEM Ports NS
European Regional Development Fund
EUROPEAN UNION

Date: 8 November 2023

RISE Research Institutes of Sweden AB

RISE/SSPA Report : RE41199324-01-00-A, Version 3

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Preface

This report was prepared as part of the Zero Emissions Ports North Sea project, and is a deliverable under work package 3, “Port Infrastructure Challenges for Electric Vessels”, as part of the activity “Mapping and analysis of energy consumption for Strömstad harbour area users”.

Support for the project provided by the Interreg North Sea Region, co-funded by the European Union Regional Development Fund, is gratefully acknowledged.

1 Introduction

The work described in this report was carried out as part of the work package “Port Infrastructure Challenges for Electric Vessels” of the Zero Emission Ports North Sea project. It includes an investigation of the Port of Strömstad, including an overview mapping of harbour area users and energy consumption, potential for electrification of different vessel segments, and needs for existing electric and hybrid vessels. A study of the potential impact of a ferry charging station on the electric distribution grid was also carried out (see Bayati et al., 2023) as part of ZEM Ports work package 3. Infrastructure needs and challenges to support the growth of vessel electrification are identified, to work towards the goal of a zero-emission port.

1.1 Need for Zero Emission Ships

The need for zero emissions ships, similar to the need for all sectors to reduce emissions, stems mainly from the findings of climate scientists and the Paris Agreement to limit the global temperature increase to “well below” 2° Celsius this century. Connected to this top-level target and the climate crisis facing the world are many regulations, goals, incentives, and demands directed towards emissions reductions. For shipping, this includes targets and strategies from many levels, including the International Maritime Organization (IMO), the European community, national governments, and even local ports. Investors are also individually and collectively providing incentives and from the market level there are concerned consumers who demand more environmentally friendly goods and transport services. As all transport modes move to reduce emissions, shipping must follow suit, not only for the sake of the planet, but for the sake of the competitiveness of the industry which can help alleviate congestion in other modes if it can decarbonize quickly.

In the North Sea region, home to many of Europe’s deep-water ports, there is a desire to reduce the emissions of shipping both to comply with climate targets and to reduce the impacts on air quality in port areas. Thus, there is an increasing need for zero-emissions vessels to meet stricter climate targets and provide a competitive advantage.

1.2 Port infrastructure challenges for electric vessels

Ports are facing a challenge with regards to providing charging infrastructure for electric and hybrid vessels. Adequate charging infrastructure s cited as a barrier to electrification of waterborne transport in a 2017 European Commission report on Electrification of the Transport System (Meyer, 2017). Some electric vessels with short turnaround times and large batteries require very high peak charging power and this places a high demand on the electricity grids in ports. Smaller vessels such as commuter ferries and fishing vessels require lower charging power and have different requirements with regards to charging solutions and plug types. There are many factors for ports to consider if they want to provide electricity and charging solutions that will meet the needs of future users. Infrastructure put in place today should be designed so that future envisioned users can be accommodated.

1.3 Zero Emission Ports North Sea Project

The objective of the Zero Emission Ports North Sea project ('ZEM Ports NS') is to facilitate the use of zero emission fuels (electricity and hydrogen) in the North Sea Region ports and maritime sector. The project considers the role of ports as an interface between zero emission vessels and port infrastructure. It addresses the integration of zero emission fuels into the port refuelling infrastructure and local energy systems, as well as port and ship energy storage. The work included in the project for zero emission hydrogen solutions includes developing refuelling infrastructure for vessels, hydrogen bunkering and storage solutions for a fuel cell vessel and developing training for crews of vessels and staff using associated infrastructure. For electricity as a zero-emission fuel, the project assesses practical solutions that ports may take to service larger scale electric vessels and other harbour users.

The ZEM ports project investigated two case studies where ports are facing the shared challenge of integrating electricity provision for battery charging into the port refueling infrastructure. These cases are as follows:

- **Aero Municipality, Denmark**: Aero, Denmark: Aero Municipality is a small island municipality with a population of 6000. Maritime transport is crucial to this community and it has regular ferry service to connect it to other parts of Denmark. The municipality has ambitious green climate goals – it aims to be self-sufficient in renewable energy by 2025 and fossil-free by 2030. Aero's E-ferry, *Ellen*, is the world's longest ranging 100% electric ferry, capable of travelling 22 nautical miles between charges. Aero Municipality faces a challenge in providing green electricity to this vessel and to the other harbour electricity users. The electricity consumption patterns of the harbour were studied and compared to local green electricity production in the ZEM Ports NS projects. Options for energy storage at the port were also assessed.

- **Strömstad, Sweden**: Strömstad Municipality is located on the west coast of Sweden close to the Norwegian border. The urban area has a population of about 7500. The harbour has significant vessel traffic including ferries, service vessels, leisure boats, charter vessels, and fishing boats. Most vessel traffic consists of smaller vessels traversing shorter routes, typically well suited to battery electric or hybrid electric propulsion. Strömstad is also the main access point to Koster Islands, Sweden's only marine national park. Reducing impacts from vessel traffic through use of greener technologies such as battery propulsion is important to protect this unique environmental resource.

  Color Hybrid, the world's largest plug-in hybrid ship, entered into service in 2019, and sails between Sandefjord, Norway, and Strömstad, Sweden. Currently the vessel can only charge its 5 MWh battery in Sandefjord, Norway, and the charge is not sufficient for the vessel to operate for the whole journey. Strömstad municipality faces a challenge with providing charging infrastructure to this ship. Thus, Strömstad Municipality is not deriving air quality benefits as the vessel is not generally operating on batteries in Swedish waters. The short

stay of the ferry in Strömstad and the large energy needs of the vessel are particular challenges in relation to the energy grid limitations.

1.4 Aim and Scope

The aim of the work described in this report was to assess the potential needs for vessel traffic electrification in Strömstad. Both the current status and future foreseen developments for the main vessel categories were to be assessed. Possibilities and needs for development of charging infrastructure for different vessel categories were also assessed.

2 Strömstad Port Areas and Users

Strömstad Municipality, located on the west coast of Sweden close to the Norwegian border, serves a range of vessel traffic including large commercial ferry operators, public transport passenger ferries, small cargo vessels serving the island archipelago, commercial fishing vessels, and charter vessels. There is also a Swedish Coast Guard Station and a Swedish Sea Rescue Society station. An overview of the main port and harbour areas is shown in Figure 1.

Figure 1. Port and harbour areas in central Strömstad area (base aerial photo from Eniro.se)

Strömstad port has seven main areas: Bojarkilen, Kebalviken, Norra Hamnen, Södra Hamnen, Torskholmen, Myren and Hålkedalen. A description of the main vessel users and activities in each area is as follows.

2.1 Bojarkilen

Bojarkilen is foremost an area for leisure boats places owned by Strömstad municipality. Here you can find 331 of the 1674 boat places that the municipality has in total. These places do not have access to electricity (Strömstad Kommun, 2023). In the inner part of Bojarkilen there is a traditional boat builder, Nilssons Båtbyggeri. The company started in 1918 and is one of the few remaining wooden boat builders in Sweden. The boat building company, which is now run by the third generation, has a history of building row boats, gigs and smaller leisure boats.

Figure 2. Bojarkilen area, with leisure dock areas (aerial photo from Eniro.se).

In addition to the berths and the boat builder, Bojarkilen also is the location for an electric cable ferry, "Bojan", which is one of two unmanned ferries in Strömstad. The small passenger ferry transits between Canning and Kebalviken and to operate the ferry a line ferry card, which is administrated at the municipal centre, is required. The ferry shortens the walking distance to Strömstad Spa & Resort, one of the major tourist spots in town. The ferry is powered by electricity. There is also an electric-powered compressor running a bubbler to circulate the water to prevent ice build-up during winter months.

Figure 3. The electric cable ferry “Bojan” located in Bojarkilen

2.2 Kebalviken

The Kebal bay area includes leisure boat dock places maintained and rented out by the municipality of Strömstad, a private marina, and a docking space by a hotel.

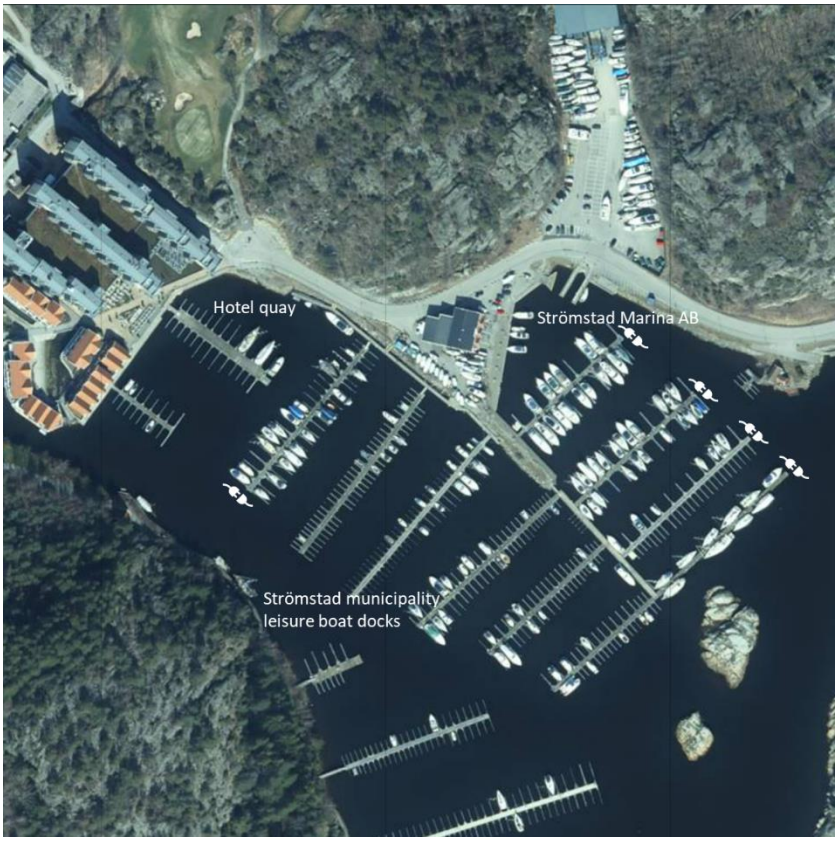

Figure 4. Kebalviken harbour area (aerial photo from Eniro.se).

The private marina, Strömstad Marina AB, provides both longer term boat docking spaces and short-term guest harbour places. Many of the dock areas for long term rental at Strömstad Marina are kept ice-free in the winter through the use of an air compressor and air bubbler lines on the seabed around the dock areas. The marina also provides boat repair and cleaning services and has a heated indoor boat storage area. One might think that the electricity consumption follows the same pattern as the tourist season, highest during the summer months, but that is not the case. This is mainly because there are customers that keep their boats in the marina year round. To heat the indoor boat storage and run the bubbler compressor to maintain the berth areas ice-free, a higher electricity consumption is needed during the winter months.

Figure 5. Electrical outlets for use by recreational boaters at Strömstad Marina AB.

Table 1. Yearly electric consumption Strömstad Marina, yearly percentage per month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
13%	13%	9%	5%	4%	6%	4%	4%	5%	9%	15%	13%

In total there are 568 boat places in Kebalviken owned by the municipality. Electricity is provided at one of the piers with a total of 56 electric outlets that can be utilised. In Kebalviken there is also a cleaning area that is open between April and October. Access to water, a hose and electrical outlet is provided, but the boat owner needs to bring their own high-pressure washer. This service is free of charge for all boat owners in Strömstad municipality.

2.3 Norra Hamnen

In the northern area of the port, Norra hamnen, there are berths for several types of passenger vessels, but no leisure vessel spaces. There are larger passenger boats for longer tours to islands in both the Swedish and Norwegian archipelago as well as smaller boats for scheduled and private tours in the archipelago. Most of the passenger traffic is seasonal. There is the possibility of electrical connection for the larger boats as well as electrical sockets at each pier for the smaller passenger boats.

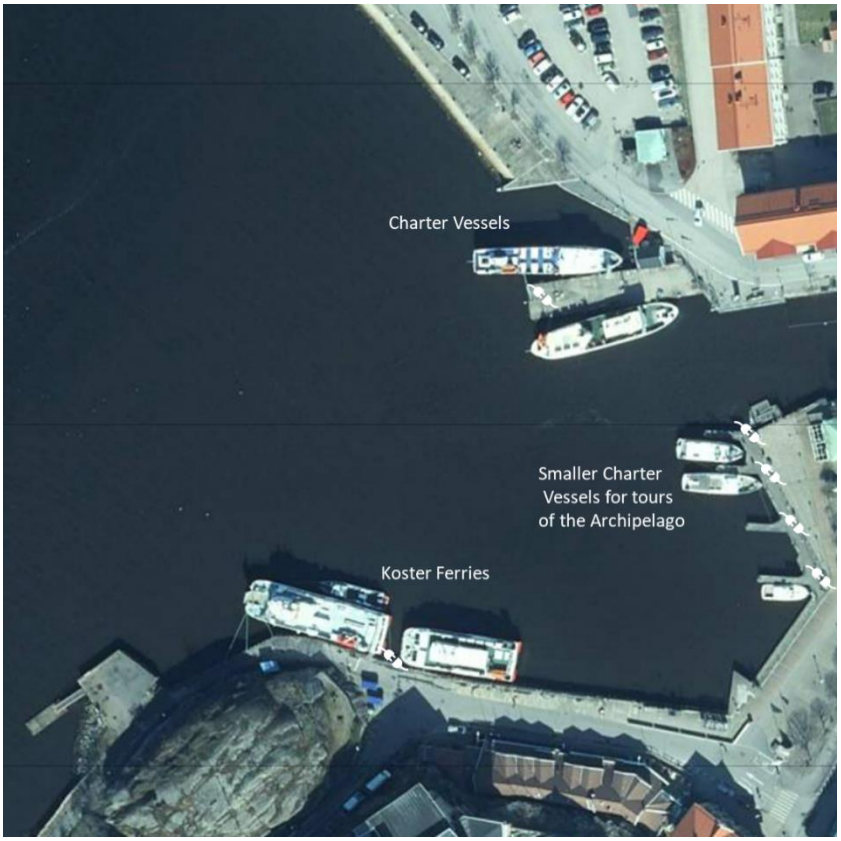

Figure 6. Norra Hamnen area (aerial photo from Eniro.se).

The northern harbour area is also a public transport hub for passenger connection to and from Koster Islands. Passenger boats to Koster are operated by Koster Marin and one of their main vessels is the electric hybrid Kostervåg. In addition to the regular electrical connections on the quayside, there is also a fast-charging station at Koster Marin's docking place that was constructed in 2023.

2.4 Södra hamnen

The south area of the port, Södra Hamnen, has leisure boats places and a guest harbour owned by Strömstad municipality. A commercial fishing boat pier is also in this area, located adjacent to the fish auction location. There are almost 300 leisure boat docks at Södra hamnen, and almost 200 of them have access to electricity. Similar to Kebalviken, a yearly fee (in this case 500 SEK) is paid to use the shore side electricity. The guest harbour shown in Figure 7 been reconstructed and can house 75 boats of different sizes in the central part of the guest harbour. Guest dock spaces are booked and paid for online, and according to the webpage, electricity is offered (Strömstad Kommun 2023b).

Figure 7. Södra Hamnen harbour area (aerial photo from Eniro.se)

At Södra hamnen there is also a pier for the commercial fishing boats. The fishermen are joint owners of the fishing association, Strömstadsfiskarnas Andelsförening. For electricity they use a system called Tallyweb where they have private codes to connect to the onshore power supply and are later billed once a month for the amount they consume. Right by the fishing boat pier there is a fish auction that provides the fishing fleet with ice and where local fish and seafood is sold.

Figure 8. TallyWeb charging infrastructure for onshore power demands.

2.5 Torskholmen

Just south of Strömstad city center is Torskholmen, a ferry terminal owned and operated by Strömstad municipality. Ferries between Strömstad and Sandefjord are operated by the shipping companies Color Line and Fjord Line. Cars are loaded onto the ferries from Torskholmen, while pedestrians board the ferry via a walkway. In 2017, a reconstruction plan of the port area was developed to accommodate the plans to introduce new, larger, and more environmentally friendly ships. In order for these new ships to still be able to arrive at Torskholmen, the ferry terminal had to be rebuilt. The refit mainly consisted of extended quays, car ramps as well as a new stair tower to accommodate the newly designed larger ships (Strömstad Kommun, 2017). It would

have to accommodate ships that are 5,000 tons heavier, 32 meters longer and have a 15-meter wider stern ramp than the boats that previously docked in the port. One of the major goals of the reconstruction was that future ships should be able to run on electricity when they are in the port (ibid.). The reconstruction was completed in 2020 at a cost of 147 250 000 SEK. In August 2019, Color Line introduced the world's largest plug-in hybrid ship with battery operation on the route. However, a charger on the Swedish side of the route has still not been installed. Normal landside electricity is however available at the ferry terminal.

Figure 9. Torskholmen harbour area (aerial photo from Eniro.se)

Skurveskär, a continuation of Strömstad municipality guest harbour, is located adjacent to Torskholmen. There are 36 berths, 20 of which are suitable for larger boats. All of these places have access to land side electricity.

2.6 Myren

The Myren harbour area includes Swedish Sea Rescue Society station, Strömstad municipality leisure boat docks, a Swedish Coast Guard Station, Koster Marine's cargo vessel services, a private marina, and a marine fueling station.

Figure 10. Myren Harbour Area (aerial photo from Eniro)

The Swedish Sea Rescue Society in Strömstad was established in 2000 and has 41 volunteers that help with various sea rescue missions. The station and rescue vessels are located at Myren harbour area. Landside electricity is available for connecting equipment or tools. Right beside the Swedish Sea Rescue Society there are approximately 170 leisure boat dock spaces owned by Strömstad municipality. These berths are for smaller boats, and during a recent renovation landside electricity connections were prepared together with the electrical lighting at the piers. However, there is no possibility to connect at most of the posts. The municipality states that there is not yet any large demand for more electrical connections at the leisure boat docks. However, it there were to be an increase of demand they are concerned that the power grid is insufficient and would need to be upgraded. The Swedish Coast Guard and Koster Marine lease land from the municipality. The Coast Guard have their main station with a land side electricity connection. Koster Marine operates their cargo vessels to transport goods out to the islands in the archipelago. They also have access to an electrical connection at their loading dock. At Myren harbour area there is also a smaller private marina called Axelssons Marin, and at the end of the harbour Strömstad municipality have a dock that can accommodate ships up to 30 000 tons.

Figure 11 – Dock lights with electrical connection possibilities at Myren leisure boat docks

2.7 Hålkedalen

Hålkedalen is a leisure boat harbour with both Strömstad municipality docks and a private marina. There are also some businesses in the area such as a construction company, boat and boat supply companies, kayak rental, accountancy company as well as a veterinarian.

Figure 12. Hålkedalen harbour area (aerial photo from Eniro.se)

The 6 piers with 180 leisure boat dock spaces are owned by Strömstad municipality. These boat spaces do not have access to electricity, apart from a few outlets at shore for simple harbour equipment. The private marina has one pier with approximately 25 dock spaces, all accommodating medium-sized vessels. Electrical outlets for land side connection is available along the pier. There is also an electrical car charger in the Hålkedalen harbour area at the building closest to the shore.

Figure 13 – Simple electrical outlets at shore in Hålkedalen

3 Vessel Traffic Patterns and Statistics

The vessel traffic in Strömstad is dominated by roll-on roll-off passenger ferries (Ro-Pax) connecting to Sandefjord, Norway, and smaller passenger ferries serving the Koster Islands. The Ro-Pax ferries call the terminal at Torskholmen and cross line 1 in Figure 14 while the ferries for the Koster Islands call Norra Hamnen and cross line 2 in Figure 14. The vessel traffic pattern shown in Figure 14 is derived from AIS data[1] from 2022. Most pleasure boats are not equipped with an AIS transponder and are thereby not included in Figure 14.

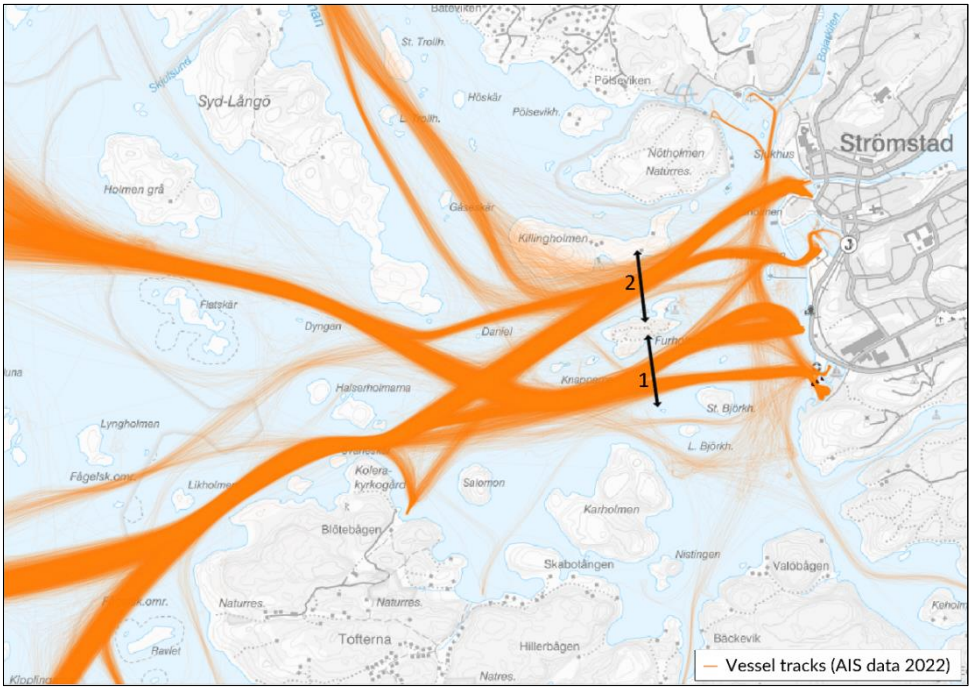

Figure 14. Vessel Traffic Patterns in Strömstad in 2022 (derived from AIS Data)

The total number of registered vessel passages across line 1 in 2022 was 5 728. Statistics on vessel types and length are shown in Figure 15. Two small deck cargo vessels supplying the Koster Islands are the only cargo vessels that regularly call at Strömstad.

[1] Automatic Identification System,

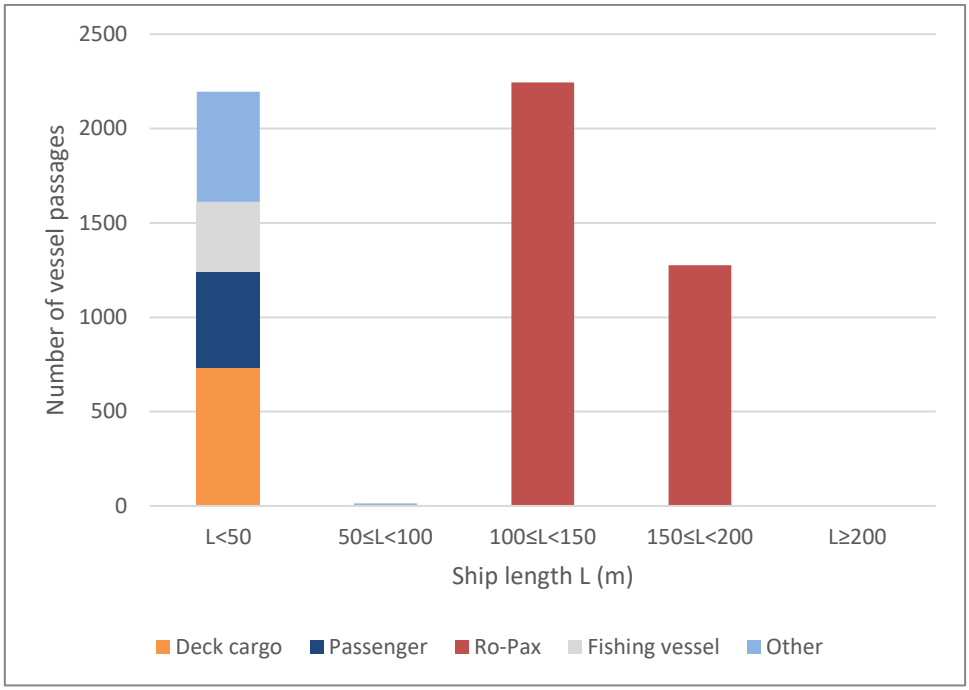

Figure 15. Passages by ship type and size for passage line 1 in 2022.

The three Ro-Pax ferries *Color Hybrid, Oslofjord* and *Color Viking* accounted for about 3 500 passages in 2022, which corresponds to about five daily departures from Strömstad. *Color Hybrid* is the largest vessel with a length of 160 m. *Oslofjord* and *Color Viking* are both about 135 m long. All other vessels passing across line 1 in 2022 had a length less than 60 m. In November 2022, *Color Viking* was sold and in 2023, only *Color Hybrid* and *Oslofjord* are operating on the route between Sandefjord and Strömstad.

The passenger ferries for the Koster Island operate frequently, especially during the summer peak season with about 20 departures daily. Figure 16 shows the number of passages across line 2 per month.

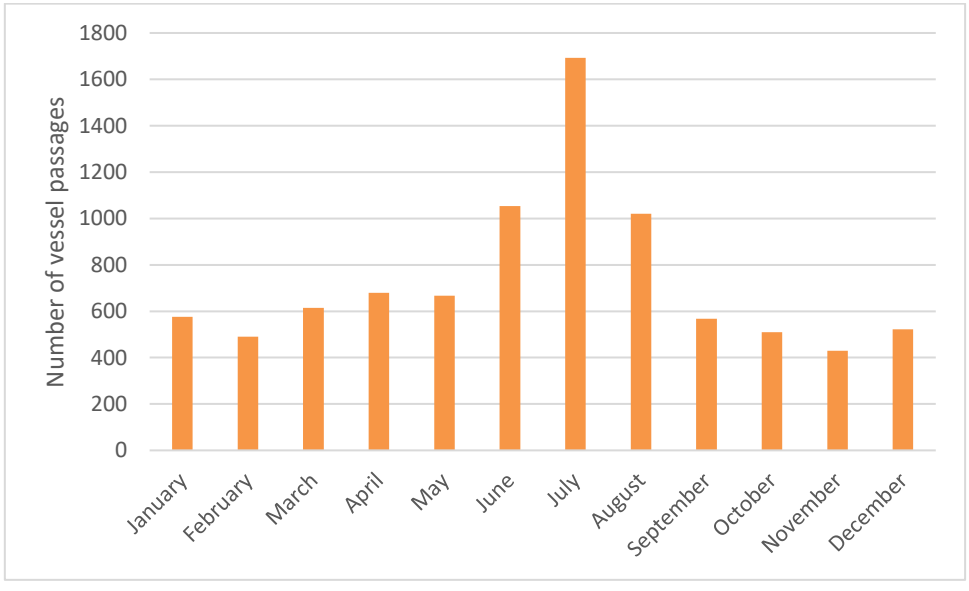

Figure 16. Number of vessel passages per month across line 2 in 2022.

Of 8 800 passages in total across line 2, five passenger ferries for the Koster Island accounted for 6 700 passages. In addition, a passenger vessel, *Vesleo II*, operating regularly between Strömstad and Hvaler, Norway, passes across line 2. In 2022 Vesleo II accounted for 800 passages.

Fishing boats also call the harbor frequently, mostly using routes across line 2. In 2022, the number of passages of fishing boats across line 2 was 925 and 370 passages across line 1.

Ship type *other* in the statistics mainly consists of the Swedish Sea Rescue Society's small boats for search and rescue (SAR) operations. Ship type o*ther* also includes tug boats, small police boats and small service vessels.

4 Vessel Energy Use and Electrification Potential

This chapter describes the propulsion system and fuel used by each main vessel category calling Strömstad harbour. The potential for electrification is also discussed for each vessel type.

4.1 Leisure Boats

Strömstad Municipality has approximately 1700 dock places for long term rentals for leisure boats. Additional it has approximately 300 guest harbour spaces.

A 2020 survey of the leisure boat segment in Sweden showed that 4% of leisure boats to have electric motors whereas for previous years the result had been zero (Swedish Transport Agency, 2021), as shown in Figure 17. More than 60% of leisure vessels have gasoline engines.

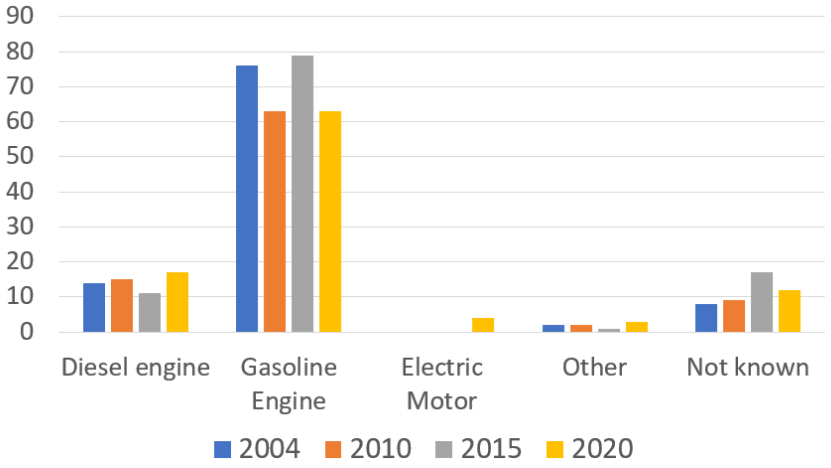

Figure 17. Type of engine in Swedish leisure boats (%). Created with data from: Swedish Transport Agency. Båtlivsundersökningen 2020, 2015, 2010 and 2004. Available: https://transportstyrelsen.se/batlivsundersokning

Electrical outlets are available in many of Strömstad's guest harbours and some leisure boat home harbours, intended for running equipment while docked - infrastructure is not yet available for charging purposes. Although vessels with small batteries could charge overnight using the same outlets as used for equipment if the connections were suitable. However, in most of the municipality's leisure boat home harbours with long term rentals, the access to outlets is limited and shared among a number of vessel dock spaces.

A recent study (Saxberg et al., 2021) carried out in Sweden predicted that the initial growth in the electrification of the leisure boat sector will be for smaller electric boats and converted sailboats, with battery capacity up to about 50 kWh. The price for larger electric boats was considered too high at present time to result in a significant increase in this segment.

Development of charging infrastructure for the emerging battery electric leisure boat sector is facing challenges from lack of standards and uncertainty regarding market growth, as well as funding for the green transition.

4.2 Fishing Boats

The commercial fishing boats operate from Södra hamnen. As previously mentioned, in 2022 there were 925 passages across line 2 and 370 passages across line 1 by fishing vessels. Twenty-two different fishing boats passed in and out of the harbour in Strömstad. However, out of those, only 5 vessels accounted for almost 60 percent of the passages. Most of them are relatively small with length of 9 m – 18 m. Only one had a length over 20 m. The most frequent fishing vessel was the 12 m long *SD623 Dagny* followed by *SD539 Gryning* at 15 m.

Figure 18. SD623 Dagny
(Photo: Magnus Bergstrand)

Figure 19.SD539 Gryning
(Photo: Donald McKay)

Figure 20 depicts fishing vessel movements in the Strömstad area during 2022. Compared to ferries or tour boats that often follow the same route, fishing boats have a more scattered movement pattern.

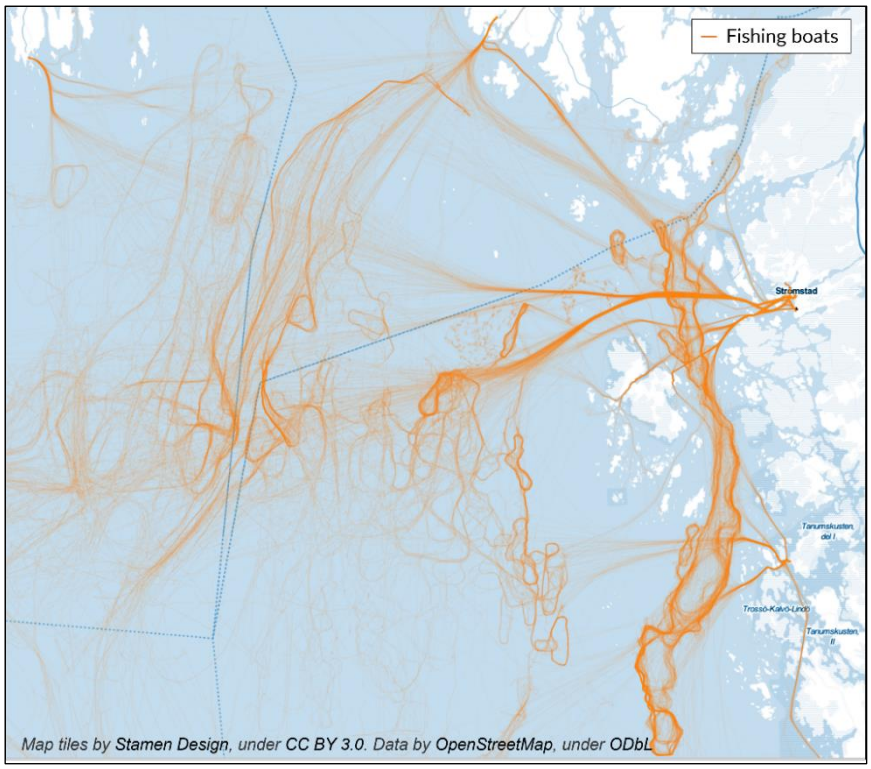

Figure 20. Tracks from fishing boats that called in Strömstad during 2022.

All fishing vessels in Strömstad area have propulsion systems that are powered by fossil fuels. This makes them increasingly vulnerable to both rising fuel prices and to requirements to reduce their greenhouse gas emissions (Ziegler & Hornborg, 2023). However, during interviews with fishers at Strömstad they stated that a transition to alternative fuels will not take place in the near future. Foremost the investment cost for the small, in many cases family owned, fishing companies is too high. They state that diesel is the most reliable fuel and also the best in terms of cost. But the preference for diesel fuel also seems to be based on tradition and culture based on statements like “we fishermen are loyal to diesel”.

4.3 Coast Guard

The Swedish coast guard has a station in the Myren harbour, in the south of Strömstad port. The station includes a surveillance vessel, KBV 310, which has a length of 20 m and was built in 1997, see Figure 21.

Figure 21. The surveillance vessel *KBV 310* is based at the Coast Guard station in Strömstad.

The vessel is part of the so-called 301 series which consists of 10 vessels, all having conventional propulsion. The average fuel consumption for each vessel in the series is about 50 tons diesel per year (Swedish Coast Guard, 2021).

The 301 series is getting old and there are plans to replace them with new slightly larger vessels at the end of 2024. The Swedish Coast Guard has concluded that none of their vessels are suitable for electric propulsion as it is not compatible with the operational requirements (Swedish Coast Guard, 2021). The new vessels with a displacement of 53 tonnes, called the 320 series, will therefore be equipped with diesel engines.

The state has placed a requirement on the Coast Guard to reduce their emissions of greenhouse gases. The reductions should be in line with the national climate targets for the transport sector which implies a reduction of greenhouse gases of 70% by 2030 and to be fossil free until 2045. To meet these goals the new vessels will use hydrogenated vegetable oil (HVO) instead of conventional diesel. According to the Swedish Coast Guard, the vessels may be converted to electric propulsion after the mid-term modification, around 2038, if battery technology has advanced sufficiently (Swedish Coast Guard, 2021).

4.4 Sea Rescue Society

The Swedish Sea Rescue Society (Sjöraddningssällskap) is a volunteer organization that is involved in approximately 90 percent of all sea rescues in Sweden. In Strömstad municipality it operates a sea rescue station located in the Myren harbour area, where it carries out approximately 300 missions per year (Sjöraddningsskällskapet, n.d.).

There are two vessels operating out of the Strömstad Rescue Station. The first one is *Rescue Roger Hansson*: an 8.4 metre long rescue boat with a 3.2 ton displacement, 34 knot speed. The second one is *Rescue Länsförsäkringar Göteborg och Bohuslän* with vessel length 11.4 metres and a displacement of 13 tons.

Figure 23. *Rescue Roger Hansson* (vessel with yellow superstructure).

Figure 22. *Rescue Länsförsäkringar Göteborg och Bohuslän*, with barge for environmental clean-up shown on shore in the background

There is also an aluminium barge (not self-propelled), approximately 10 metres long with a displacement of 2.5 tons (Sjöraddningsskällskapet, n.d. 1). The barge is used for assistance in environmental clean-up activities – for example it may be used to transport floating booms capable of containing spilled oil or debris.

The SSRS have allocated funds to investigate improving the environmental performance of their vessels. They have initiated a project, ELINN (Electric-Innovation), where a prototype 9 metre electrific hydrofoil rigid inflatable boat (RIB) is being designed, built, and tested (RISE, 2022). The project will run until 2026 (Sjöraddningsskällskapet, n.d. 2). SSRA are also investigating charging potential for vessels at their stations, and whether electrical upgrades would be required.

4.5 Public Transport Ferries

Public transport passenger ferry service connects Strömstad with the Koster Islands. The ferry service is part of Västra Götaland Region's public transport network and is operated by Koster Marin under contract to Västtrafik. The Koster Islands is an archipelago located about 10 kilometres west of Strömstad. The ferry route takes about 1.5 hours for a round trip, with five stops along the way. During the winter there are six to seven sailings per weekday, which can be managed by one vessel. During the high season in the summer two or three vessels are needed to meet the demand, with up to twenty departures per day from Strömstad.

Västra Götaland Region has set ambitious climate goals, requiring an 80% reduction of greenhouse gas emissions by 2030, compared to 1990 levels. Västtrafik, the organization responsible for public transport in the region, has required reductions in CO_2 emissions as part of the procurement process for services including those to Koster Islands.

As a result of requirements for reduced emissions, Koster Marin decided to convert one of their vessesl, *Kostervåg,* to battery hybrid operation. The converted vessel, with a length of 30 meters and a breadth of 9 metres, entered service in 2022. It can carry 270 passengers. The 782 kWh battery pack on the vessel can be fully charged overnight using standard 63 amps 400 V electricity supply.

Figure 24. The converted passenger vessel *Kostervåg* at the quayside in Strömstad's north harbour area

The cost to rebuild the *Kostervåg* to electric propulsion was about 30 million SEK (Sörensen Lund, 2022). Koster Marin received some financial support for the conversion of the vessel, through the Swedish national program "Klimatklivet", which provides support to measures that reduce greenhouse gas emissions (Sjöstrand and Lindgren, 2022).

Construction of a fast charger in Strömstad's north harbour was completed in March 2023. It can supply the *Kostervåg* with 250 kWh of electricity in 15 minutes, enough for one round trip, so the vessel can now operate fully on battery power the entire day (Eriksson, 2023). The charging infrastructure transforms electricity to 750 kW DC, and has 1000 kW charging effect.

Figure 25. Charging infrastructure for the *Kostervåg* in Strömstad's north harbour – transformer station on the left and charging tower on the right

The costs for the infrastructure for the fast charging station (transformer station, charging tower, planning, and construction) was about 12 million SEK (Västtrafik, 2022) (see also Chapter 6).

4.6 RoPax Ferries

Two ferry companies, Color Line and Fjord Line, provide transport services on the 10 kilometre long route between Strömstad, Sweden, and Sandefjord, Norway. The RoPax ferries sailing on this route are the largest vessels to call at Strömstad and call at the port year-round. Their crossing time is about two and a half hours with sailing speeds of about 15 knots in open water. They share the ferry terminal and quay side mooring location operated by Strömstad municipality, and thus only one may be in port at a given time.

4.6.1 Color Line

Color Line's *Color Hybrid* ferry was the world's largest plug-in hybrid when it launched in 2019 (Moore, 2019). The 160 metre long vessel has capacity for 2000 passengers and 500 cars. Sandefjord municipality requested emission-free sailing, with low noise also being a priority (Moore, 2019), when deciding which operator would receive the concession for the 10 AM sailing slot to Strömstad. Color Line commissioned the battery electric hybrid *Color Hybrid* to be awarded the concession.

The *Color Hybrid* can operate for about 60 minutes at speeds up to 12.5 knots with the 5 MWh batteries that are installed on board (Moore, 2019). The vessel uses diesel electric propulsion, and has four diesel engines on board, that can be run at optimal loads with the batteries providing peak shaving. The diesel engines power two electric motors. Currently the vessel can only charge its battery in Sandefjord, and because the crossing time to Strömstad is about two and a half hours, full battery operation is used primarily when sailing in and out of the Sandefjord area.

The *Color Viking*, a 137 metre long vessel built in 1985, also was used for some sailings on the Strömstad-Sandefjord route in 2021 and 2022, although the *Color Hybrid* was used for more of the crossings in 2022. The *Color Viking* was sold in late 2022 and in 2023 the route has been operated only with the *Color Hybrid*.

4.6.2 Fjord Line

The MS *Oslofjord* (see Figure 26) is operated by Fjord Line on the Sandefjord-Strömstad crossing. It has a length overall of 134 metres and a gross tonnage of 17851. It can carry approximately 1350 passengers and 370 cars (Fjord Line, 2023). The ship was built in 2014 and burns conventional fuel oil in two four-stroke engines for propulsion. It typically makes two round-trip voyages per day from Sandefjord to Strömstad and carries around 400 000 passengers per year (Fjord Line, 2023).

Figure 26. MS *Oslofjord* approaching Strömstad harbour

4.7 Charter Vessels

There are a few charter passenger vessels operating from Strömstad's north harbour during the spring/summer season. The *Vesleo II*, a Norwegian passenger vessel, is operated out of Strömstad by Nadir Hvaler Fjordcruise. During 2023 it travelled regularly from Strömstad to Skjaerhalden on the island Kirkeøy (see Figure 27). The 33 metre long passenger vessel was built in 1980 and sails under the Norwegian flag. It is propelled by two Scania engines running on diesel distillate fuel.

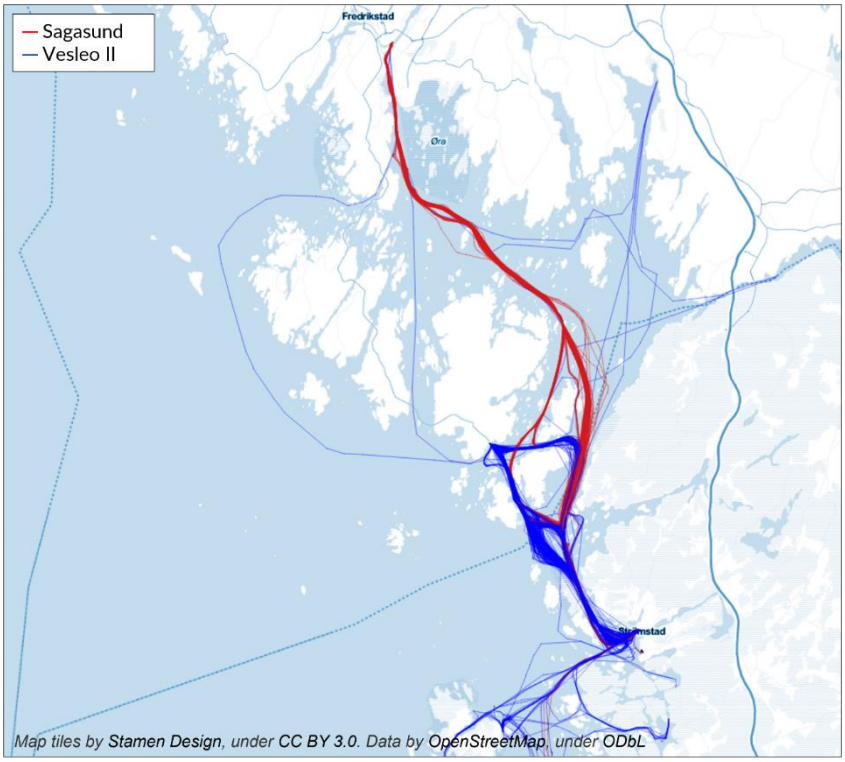

Figure 27. Route travelled by charter vessel *Vesleo II* shown in blue (AIS data from 2022)

Selin Charter AB, a Swedish charter operator, takes passengers from Strömstad to areas in the Koster Sea Marine National Park and the nearby islands such as Nord Långö. Vessels operated by Selin Charter include the M/S *Sara* (see Figure 28) and M/S *Kosterskär*.

Figure 28. Charter Vessel M/S *Sara*

4.8 Cargo Vessels

There are two deck cargo vessels operated out of Strömstad by Koster Marin – they are sister vessels built in 1957, as follows:

Kosterfärjan (see Figure 29):

- Length 28 metres; beam 8 meters

Kosterfärjan 4:

- Length 28 metres; beam 8 metres

(information from: https://kostermarin.se/fartyg/)

Both are equipped with hydraulic cranes for cargo handling, and have ramps for loading road vehicles. They use Scania propulsion engines that run on diesel distillate fuel. They provide services to the Koster Islands, transporting goods and vehicles. *Kosterfärjan 4* provides the majority of the regularly scheduled transport service, as it has more adaptations for transporting goods than the *Kosterfärjan*, including a larger crane and 30% more capacity for refrigerated goods (Koster Marin, n.d.). Figure 31 shows the *Kosterfärjan 4* vessel movements in 2022, according to vessel AIS data.

Figure 29. *Kosterfärjan*

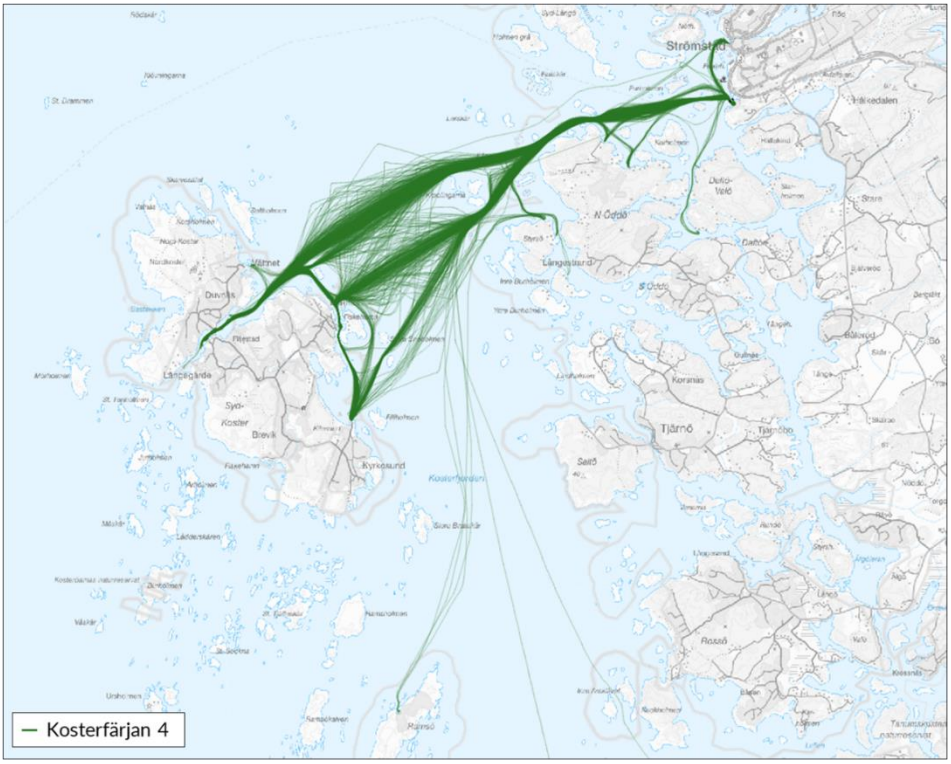

Figure 30. *Kosterfärjan 4* tracks from AIS data for 2022

5 Reduced GHG Emissions from electric and hybrid vessels in Strömstad

Most vessel traffic in Strömstad consists of smaller vessels traversing shorter routes, typically well suited to battery electric or hybrid electric propulsion. As of 2023, however, there were only two vessels with electric or hybrid propulsion operating out of the port, plus the electric unmanned cable ferry at Boyarkilen. The “first movers” towards electric propulsion in Strömstad are within the passenger ferry segment, which is also the case for most other fully electric or hybrid vessels in other parts of Northern Europe. The estimated and potential GHG emissions reductions achievable with operation of electric and hybrid vessels in Strömstad are described as follows. The potential for leisure vessel electrification is also discussed.

5.1 Public Transport Ferries

With electrification of the of the passenger ferry *Kostervåg*, Koster Marin estimates the CO_2 emissions reductions to be 700 tonnes per year, compared to operation on distillate fuel (Sörensen Lund, 2022). Further reductions could be achieved with use of battery electric propulsion for other ferries operating on the route. There may be a requirement for this in the future from the Västra Götalands region, to meet targets for emissions reductions by 2030.

5.2 RoPax Ferries

The RoPax ferry *Color Hybrid* has a battery capacity of 5 MWh. The ferry is charged in Sandefjord and the battery capacity is used for maneuvering in and out of Sandefjord, as well as for peak shaving to facilitate operation of the diesel engines in their most efficient range. If the batteries could be charged in Strömstad as well, the vessel would operate on electricity in and out of Strömstad. The fuel saving potential for charging in Strömstad is estimated to 200 tons diesel per year based on information from Color Line. The fuel saving corresponds to emission reduction of 710 tons CO_2-equivalents per year.

A comparison of CO_2 and fuel consumption per nautical mile for the three large RoPax vessels calling Strömstad in 2021, shown in Table 2, indicates that the *Color Hybrid* has the fuel lowest consumption and CO_2 emissions per nautical mile of the three RoPax vessels that travelled the route that year. Noting that the emissions per nautical mile are about 40% lower than the *Color Viking*, the older vessel, and about 15% lower than those from the MS *Oslofjord*. During 2021, there were still some travel restrictions due to the COVID 19 pandemic, so the total fuel use and emissions shown may not be representative of a normal travel year. However, the data shows that there is the potential for significant CO_2 reductions if ferries with additional battery capacity were operating the route.

Table 2. Selected data on fuel consumption and emissions for the RoPax vessels operating on the Sandefjord to Strömstad route in 2021. [2]

	Annual time at Sea (hrs)	Total Fuel Consumption (m tonnes)	Total CO2 Emissions (m tonnes)	Annual avg. fuel consumption (kg/n mile)	Annual avg. CO2 Emissions (kg/n mile)
Color Viking	460	869	2787	132.7	425.4
Color Hybrid	1750	2079	6665	82.5	264.5
MS Oslofjord	2135	2553	8184	97.4	312.2

5.3 Leisure Boats

Regarding leisure boats, data on fuel use and associated emissions for specific harbour areas such as Strömstad is not available. For Sweden as a whole, however, greenhouse gas emissions from leisure boats was estimated to be 179 000 tons CO_2 equivalents per year (Moksnes et al., 2019, using data from 2017). Compared to other transport modes this is significant – for example it is about 30% of the estimated greenhouse gas emissions from all Swedish domestic flights per year (Moksnes et al., 2019). Thus electrification within the leisure boat sector could potentially have an important impact.

[2] Monitoring, reporting and verification (MRV) Regulation 2015/757 (as amended by Delegated Regulation 2016/2071. Data is from the EU's Monitoring, Reporting, and Verification (MRV2) THETIS-MRV database, which requires all vessels above 5000 gross tonnage calling at EU ports to report annually.

6 Electricity Provision from the Port

Within the Port of Strömstad the only designated vessel charger as of 2023 was for the public transport ferry Kostervåg. The electrical system upgrade and fast charging equipment procurement for the infrastructure in the north harbour of Strömstad for the Koster ferry (*Kostervåg*) was carried out by Västtrafik, which is the organization responsible for public transport in the Västra Götaland region of Sweden. The cost for the infrastructure was estimated to be 12 million Swedish crowns (SEK) in 2022 (Västtrafik, 2022). This included the electrical network station, the charging equipment, planning, and construction costs. Västtrafik received grants totalling 6.5 million SEK from and invested 5.5 million SEK from their own budget.

Fast charging of large batteries such as those on electric powered ferries requires relatively high power to be transferred from power lines and transformers. ZEM Ports project partner University of Southern Denmark carried out a modelling study on the Kostervåg ferry fast charging station's impact on the electricity distribution system. The investigation by Bayati et al. (2023) modelled direct power loss costs and the indirect costs of increased electrical system infrastructure aging. Methods to reduce the impact of the fast charging station on the electric system grid components included re-scheduling e-ferry departures, installing photovoltaics, and energy storage.

To enable charging for the *Color Hybrid*, investigations and negotiations were carried out as early as 2018. The ferry is moored in Strömstad for about 50 min at each call; due to the limited time the charging requires a power of 6,5 MW. A charging station for *Color Hybrid* therefore requires an extensive reinforcement of the electricity grid down to the quay in Strömstad. The investment cost for the charging facility, including grid extension, was estimated to about 11 million SEK in 2019.

Regarding electricity supply for the emerging electrified leisure boat sector, a study carried out for the west coast of Sweden (Saxberg et al., 2021) considered that the initial focus should be on infrastructure for overnight charging at long-term rental boat places. With overnight charging, relatively small changes to infrastructure, without the need for grid strengthening, would suffice. There has been an increase in the amount of electronic equipment on board vessels over time, as well as with the use of electrical tools for vessel care and maintenance (Saxbert et al., 2021). Thus the provision of electrical outlets at leisure boat harbours has been increasing. Over the longer term, as the price of larger battery electric vessels decreases or if incentives are available, the need for fast charging during the daytime would develop. This would place a higher demand on upgrading the electrical infrastructure for leisure boat quays as well.

7 Discussion and conclusions

Electrification of vessels operating in Strömstad would be a great step towards a North Sea Region with reduced GHG emissions, minimized noise pollution and enhanced sustainability. To move towards electrification as a solution for zero emission ship operations there are a number of challenges to overcome. There are obstacles and opportunities both for the vessel electrification and the provision of charging infrastructure at the port. Economic, operational, technological, and organizational challenges identified during the case study are discussed below.

7.1 Economic Challenges with Electrification

Vessels:

Electrification of a fleet requires a large capital investment. Either new boats must be purchased, or current vessels must be rebuilt or retrofitted. Investment costs are large for any ship operator, but can be particularly challenging for smaller vessel operators such as many of those operating in Strömstad. Grants may be available for some commercial vessel types, but **significant own financing** will be needed to invest in a new or converted vessel.

Even if the specific vessel electrification project may be eligible for funding; **the grant application process may be difficult**. Many companies need to hire specialists to complete the process successfully. This may make it more difficult for smaller operators that do not have the same financial stability or in-house expertise as larger companies.

When making such a large investment it is important to fully investigate the business case. Comparisons should be made between alternatives required to meet emissions reduction targets, and to be able to calculate the payback times. However, there is **uncertainty regarding alternatives** (future fuel and renewable electricity prices, operating contract conditions, etc.) which makes the process and decision-making more challenging.

New regulations are being developed for large commercial vessels regarding energy efficiency and emissions. Targets are being developed at international, regional, national, and organizational levels, with public transport being a key area. However, there are currently **no incentives or targets for some segments such as leisure vessels or commercial fishing vessels**. Without incentives or requirements in place, change could be slow.

Charging Infrastructure:

Strengthening of the electrical grid is often required for fast charging and can be costly and difficult to finance. This was experienced by the Port of Strömstad when attempting to put in place fast charging for the *Color Hybrid*. Additionally fast charging stations can result in accelerated aging and power losses for the distribution grid (Bayati et al., 2023). An alternative to grid strengthening that may be preferable for some cases is to install shore-based Energy Storage Systems (ESS). This was investigated as part of the case study on battery electric ferries on the Island of

Ærø (Mikkelsen, 2023), conducted as part of the ZEM Ports NS project. For some scenarios this option was found to have both economic and socio-economic benefits.

7.2 Operational Challenges with Electrification

Vessels:

When changing to electric or hybrid vessels, **the technology is new for most operators and crew**. Therefore, training is required to understand the new way of operating the vessel. This must be planned for and carried out at the right time, and include the right personnel.

Charging Infrastructure:

Charging the battery pack can add **additional workload** for the crew members when manual connection is carried out, such as the case of the Koster ferry, and could be challenging for shorter stays in port, when the crew also have loading and unloading activities to carry out. Automated connection for fast charging, such as is done for the e-ferry Ellen in Ærø, would not normally have an impact on workload.

Not only is training needed for the operation of the electric vessel at sea, **the new charging technology requires training** as well.

Since many vessels operate according to a fixed schedule with short stops in port, fast chargers are required. To do so, **grid strengthening is needed.** Grid stability and power availability during peak periods needs to be considered to ensure reliable charging of the vessels. As mentioned, provision of shore-based ESS is an alternative to grid strengthening.

7.3 Technical Challenges with Electrification

Vessels:

The **limited energy density and storage capacity of current battery technologies** are a big challenge for electrification of vessels with longer range. Development of higher energy density batteries will help extend the range and performance of electric vessels.

Technology is still under development for electrification of vessels. Most solutions are still custom to the vessel and specific route/service type. This makes it both more time consuming and costly to implement the new solutions as compared to traditional technology. However, as more vessels are electrified and experience is gained, the costs and difficulties will be reduced. Maturation of the technology has already started to occur.

Charging Infrastructure:

Regarding the charging infrastructure there are **few implemented standards**. Investment costs for charging stations are high and most can only be used for specific vessel solutions. Standards are still being developed.

7.4 Organisational Challenges with Electrification

Charging Infrastructure:

Since there are large investments for the charging infrastructure the cost might be shared between different actors. A challenge is therefore to develop a **cost-sharing structure**. Who pays for grid strengthening or on-shore energy storage? Who pays for the charging tower?

Large charging infrastructures might **disrupt shoreline views and aesthetics**. In many cases the installation will need approval from the municipality, as was the case for the *Kostervåg* fast charging tower installed in Strömstad. This might take additional time and resources.

8 Summary

An investigation of the needs and challenges with electrification of vessel types operating in Strömstad, Sweden, was carried out, as part of the work in the ZEM Ports North Sea project focused on port infrastructure challenges for electric vessels.

There has been significant development in battery electric vessels in recent years in the North Sea Region. Most vessels are in the passenger ferry segment, with two examples in Strömstad. These include the *Color Hybrid*, a newbuild large RoPax ferry transiting the Strömstad-Sandefjord route, and the public transport passenger ferry *Kostervåg*, which was converted to battery hybrid operation in 2022. For both of these vessel operators, there was external influence/incentive for choosing battery hybrid operation. For the *Kostervåg*, the public transport authority contracting the service had set targets for greenhouse gas emissions reductions. The choice of electrification to achieve this goal has had benefits for Koster Marine compared to other emissions reductions options. Although it required a higher investment than simply replacing fossil fuel with a renewable fuel option such as hydrogenated vegetable oil (HVO), there have been benefits including reduced noise and positive feedback from crew and passengers, lower maintenance expected, and the working environment is improved as compared to using an alternative fuel with an internal combustion engine. Additionally the energy use for the vessel has been reduced due to increased awareness of energy use at higher speeds, due to monitoring of the battery state and charging requirements. The price of electricity was also significantly lower than the comparable price on an energy basis for HVO.

For the *Color Hybrid*, the incentive for battery hybrid operation came from the municipality of Sandefjord, which prioritized emission-free sailing in the port area and low noise when awarding the commission for the more desirable sailing departure times from the port. Clearly incentives and requirements are important for convincing vessel operators to choose lower GHG emission solutions.

Regarding charging infrastructure, it was installed successfully for the Koster public transport passenger ferry, with the costs covered by the regional public transport agency and through a grant for emission reductions. For the *Color Hybrid*, Strömstad municipality has not to date been able to raise sufficient funds to pay for the costly grid extension required. It is challenging for a small municipality and difficult to obtain grants due to the complications with claiming only CO_2 savings for part of the voyage requirements.

Challenges with establishing vessel infrastructure charging for the ferries in Strömstad included obtaining financing, insufficient electrical grid to support fast charging, and need for custom solutions for each vessel. A fast charging station can accelerate aging of the electric distribution system and result in power system losses, but this can be reduced through measures such as adding photovoltaics, battery storage, or re-scheduling of vessel charging times (Bayati et al., 2023).

Development of charging infrastructure for the developing leisure boat sector is facing challenges from lack of standards and uncertainty regarding market growth, as well as funding for the green transition.

Electrical grid strengthening and energy storage systems in the main port areas are options to consider for meeting future needs. More electrification of the sector will help achieve the goal of a zero emission port.

Regarding the way forward for further electrification of vessels and provision of supporting infrastructure, the following can be summarized from the Strömstad case:

- Support and financing are need for both vessel operators and those providing charging infrastructure and grid strengthening, as investments are large
- Regulations, policies, or incentives requiring reduced vessel emissions are important for action.

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