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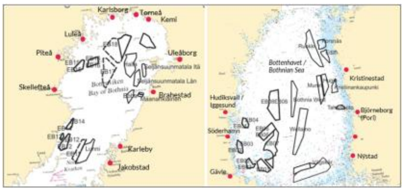
Estimation of costs and resource requirements regarding the impact of offshore wind power on winter navigation in the Gulf of Bothnia



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Summary and recommendations

The development of offshore wind power within the designated energy areas included in the analysis will result in longer routes for both icebreakers and commercial shipping, and will likely also require changes in operational patterns, as current routes will need to be partially adjusted due to the wind farms. This leads to an increase in need for icebreaking, which is both a resource and cost issue. To identify solutions for coexistence, it is necessary to analyse the impacts on winter navigation, for example in terms of route deviations, fuel consumption, and associated emissions. In addition, a socio-economic assessment must be conducted regarding offshore wind power and compared with the impacts on winter navigation.

The assignment is conducted on behalf of the Swedish Maritime Administration and financed by the Swedish Energy Agency.

The analysis covers predicted maritime traffic in the Bothnian Sea and Bay of Bothnia in the year 2030 and is based on a number of energy areas defined in consultation with the Swedish Energy Agency, the Swedish Maritime Administration, and the Finnish maritime authorities. The energy areas located within Swedish territorial waters and the Swedish EEZ have an estimated LCOE below the median value of 98 EUR/MWh, according to the supporting report *Proposal for Suitable Energy Extraction Areas for the Marine Spatial Plans*, prepared by the Swedish Energy Agency in 2023. This corresponds to Scenario 1 in the analysis. In addition, the Swedish Maritime Administration has chosen to include a further scenario, Scenario 2, which covers three additional energy production areas in the Bay of Bothnia, regardless of the LCOE in these additional areas. The reason for including this additional analysis is the special sea ice conditions in the Bay of Bothnia, and the fact that the impact from a development in the additional areas on icebreaking operations could be significant. However, it is unlikely that all the areas included in the analysis will be developed with wind power, even in Scenario 1, and also unlikely that the entire energy production areas set out to be developable would in fact be developed.

The scenarios in the analysis are based on statistics from the winter seasons 2010/2011, 2017/2018, 2019/2020, and 2023/2024, covering all types of winters – mild, normal, and severe – with corresponding variations in ice coverage and the need for assistance. In addition to the estimated impacts on icebreaking and commercial shipping during a normal winter, the study also presents a ten-year average, based on the assumption that a ten-year period includes one severe winter, five normal winters, and four mild winters.

Route extensions and increased fuel costs have been calculated for shipping routes to several ports, selected in consultation with the Swedish Maritime Administration. The ports included in the Bothnian Sea are Gävle, Söderhamn, and Iggesund/Hudiksvall, as well as Kaskinen, Pori, and Uusikaupunki. The ports included in the Bay of Bothnia are Skellefteå, Haraholmen/Piteå,

Luleå, Karlsborg, Pietarsaari, Kokkola, Raahe, Oulu, and Kemi. Current routes have been identified using AIS data, and today's route distances have been calculated based on example routes derived from relevant data. In the Bay of Bothnia, wind direction has been considered, as ice conditions and the availability of navigable passages are strongly affected by wind. Future example routes have been defined together with senior Swedish icebreaker officers.

Up to 2030, predicted traffic growth to the analysed ports is approximately 30 %. A baseline scenario (Scenario 0) for routes and assistance distances has been calculated, which considers only the effects of traffic growth. According to Scenario 0, the need for icebreaker assistance in the Bay of Bothnia will increase by approximately 74 % compared to today's example routes. Traffic growth itself has a greater impact on future icebreaking assistance distances, and thus fuel consumption and emissions, than the additional distances caused by the development of wind farms within the analysed energy areas. In Scenario 1, the calculated assistance distance increases by an additional 36 % relative to Scenario 0, and in Scenario 2 the corresponding increase is 43 %. For commercial shipping in the Bay of Bothnia, the route extensions are small. However, vessels may still need to take, or be directed to, a partly different route compared with today, and that route may involve more difficult conditions than the original one. However, commercial vessels are only directed to routes that are navigable, and the impact of wind farm development in the Bay of Bothnia will primarily affect icebreaking operations.

In the Bothnian Sea, the opposite applies: commercial shipping is affected to a significantly greater extent than icebreaking operations if all energy areas included in the analysis are developed with wind farms. This is mainly due to the number and extent of energy areas in the southwestern Bothnian Sea, which altogether cause substantial route extensions for commercial shipping, corresponding to an estimated distance increase of approximately 50 %, based on example routes. Longer routes result in higher fuel consumption, higher emissions, and longer transit times. The additional assistance distance for icebreakers due to wind farm development is minor because extensive and long-lasting sea ice conditions rarely occur in the Bothnian Sea. The additional assistance distance is estimated to amount to only about 800 nautical miles per year as per the ten-year average.

The socio-economic assessment included in the analysis, taking into account renewable electricity production, avoided CO_2 emissions, employment opportunities, and operation and maintenance, implies that the societal benefits of offshore wind power, assuming full development of all energy areas in the analysis, by far exceed the costs for winter navigation. Even when considering the investment cost for building wind farms, currently borne solely by wind power developers, the total societal benefits are estimated to be about four times higher the combined increased cost of winter navigation and the investment cost of wind farms. The investment cost for new icebreakers is not included in the calculations. Additional icebreaking resources are expected to be required, but primarily to manage the predicted traffic growth toward 2030. Offshore wind development may impose further resource needs, depending on which energy areas are developed.

Currently, due to high investment costs and major uncertainties related to electricity price developments, the market for offshore wind power in Sweden and Finland has slowed down. The present permitting process, with long lead times and significant uncertainties, may also be a contributing factor. There are no joint recommendations between Sweden and Finland regarding the establishment of adjacent wind farms close to the border, particularly regarding appropriate spacing between wind farms. Furthermore, there are no recommendations for the establishment of adjacent wind farms or a comprehensive framework for assessing multiple offshore wind farms within a single maritime area. There is a need for coordination of guidelines between Sweden and Finland for establishing wind farms close to the EEZ boundary. Joint guidelines for suitable corridor widths between adjacent wind farms should also be developed. Furthermore, the planning and permit process need to revised and coordinated.

The allocation of costs is not covered by this analysis but concerns several different stakeholders, in different ways. The icebreaking service faces both cost and resource challenges related to predicted traffic growth and the establishment of wind power. Commercial shipping, especially in the Bothnian Sea, will need to manage cost and time implications associated with longer routes if wind farms are developed in the energy areas included in the analysis. A cost distribution should be further investigated and addressed by the relevant parties: shipping companies, ports, wind farm developers, and the state. A separate assessment should also be made regarding the significant societal benefits expected from offshore wind power, relative to the investment cost of wind farm development, in order to identify suitable risk-sharing and financing mechanisms.

For offshore wind power and winter navigation to coexist, coordination between the different interests is required.

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1 Introduction and background

There is a great interest in establishing offshore wind farms in the Bothnian Sea and the Bay of Bothnia, both areas where sea ice occurs each winter to varying degrees. In particular this applies to the Bay of Bothnia, where icebreaker assistance is required for the majority of the vessels calling northern ports during the winter season.

At present, there is a lack of detailed knowledge regarding how offshore wind farms will affect ice formation and the conditions for conducting winter navigation. The Swedish Maritime Administration and Finnish maritime authorities (Finnish Transport Infrastructure Agency and Finnish Transport and Communication Agency) assess that wind farms will influence how the ice forms and breaks, leading to deformed ice. Research on how ice formation is affected is currently ongoing. Irrespective of the direct effects on ice formation, impact on winter navigation will also occur through longer routes and a need for more and longer assistance operations, as well as a change in operational patterns. This, in turn, leads to a greater need for ice breaking, which is both a resource and cost issue.

To identify solutions for coexistence, it is of interest to weigh the production of new energy against the impact on shipping, thereby estimating the cost of coexistence. As a starting point for such considerations, it is necessary to analyse the effects on winter navigation, for example, impacts on shipping routes, fuel consumption, and the related emissions. In addition, a socioeconomic calculation needs to be made regarding the benefits of offshore wind power.

The assignment is carried out on behalf of the Swedish Maritime Administration, with funding from the Swedish Energy Agency.

1.1 Purpose

The present report aims to describe the impact of offshore wind power on winter navigation in the Bay of Bothnia and to highlight solutions that may facilitate coexistence. The analysis seeks to present the operational effects on winter navigation and how the socioeconomic costs and benefits are influenced by coexistence.

1.2 Scope and delimitation

The analysis is based on input data primarily from Swedish and Finnish maritime authorities.

The scenarios included in the analysis cover mild, normal, and severe ice winters[1], with the normal winter serving as the principal case. However, the extent of ice coverage does not provide the full picture of how manageable the ice is from an icebreaker's perspective, which is why the number of assistance operations[2] has formed the basis for selecting winters for the various scenarios. As ice coverage and the characteristics of the ice vary between different winters, even within normal winters, a combined assessment of effects has also been made regarding operational impact over a ten-year period.

For the analysis, the following seasons have been selected, and data from these winters form the basis for the calculated ten-year average:

2010/2011, representing a season with a large number of assistance operations (classified as a severe ice winter in terms of the maximum extent of sea ice).

[1] Mild, normal, and severe ice winters: The extent of the ice and the length of the ice winter vary between different years. Ice winters are classified as "mild", "normal", and "severe". The overall severity is assessed based on the maximum extent of sea ice for the entire Baltic Sea area, although the local severity in specific maritime areas may differ from the overall severity.

[2] Assistance: when one or more vessels receive help from an icebreaker.

2017/2018 and 2023/2024, representing seasons with a medium number of assistance operations (classified as normal ice winters in terms of the maximum extent of sea ice).

2019/2020, representing a season with a small number of assistance operations (classified as a mild ice winter in terms of the maximum extent of sea ice).

The length of the winter season varies depending on whether it concerns the Bothnian Sea or the Bay of Bothnia, and whether it is a winter with few or many assistance operations. For the Bothnian Sea, the analysis covers the period from 1 January to 15 April, and for the Bay of Bothnia from 1 December to 15 May.

The energy areas included have been determined in consultation with the Swedish Maritime Administration and the Swedish Energy Agency, as well as using information from the Finnish maritime authorities regarding currently planned Finnish wind farms. The basis for the analysis, in terms of wind farms included, is the background report *"Proposal for suitable energy production areas for the marine spatial plans"*, which was prepared by the Swedish Energy Agency in 2023[3] for the Swedish Agency for Marine and Water Management's work on proposing changes to the marine spatial plans. However, not all energy production areas are considered realistic to develop. Therefore, only those areas from the background report with an estimated LCOE lower than the median value of 98 EUR/MWh are included in the analysis dataset. The reason for this is that these areas are assessed to have a higher likelihood of being realized, as the profitability conditions are better compared to other areas. However, it is unlikely that all areas included in the analysis will be developed, or that the entire surface area of the assumed realizable areas will be utilised for wind power, which means the analysis essentially covers an unlikely worst-case scenario.

In addition to the above, the Swedish Maritime Administration has chosen to include an additional scenario for the Bay of Bothnia, which covers all designated energy production areas in the Bay of Bothnia, regardless of the LCOE[4] for the additional areas. The reason for this additional analysis is the prevailing conditions of sea ice in the Bay of Bothnia and the fact that the impact on icebreaking operations from the additional areas potentially could be significant.

In some areas, planned energy areas are in close proximity to one another. The analysis assumes that the layout of wind farms allows for passage between two adjacent areas. The analysis does not include determining an appropriate width for such passages.

An analysis of any increased risk of accidents due to the combination of sea ice and offshore wind power is not included in this assignment.

The energy production areas included in the analysis are shown in Figure 1.1.

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[3] https://energimyndigheten.a-w2m.se/System/TemplateView.aspx?p=Arkitektkopia&id=1e0d5b1929814bd4876b281b32ff4a30&q=f%C3%B6rslag%20p%C3%A5%20l%C3%A4mpliga&lstqty=1

[4] LCOE (Levelized cost of energy) according to Swecos report: *Indikativ analys av objektiva lönsamhetsförutsättningar för havsbaserad vindkraft* till Utredningen om havsbaserad vindkraft, 2024.

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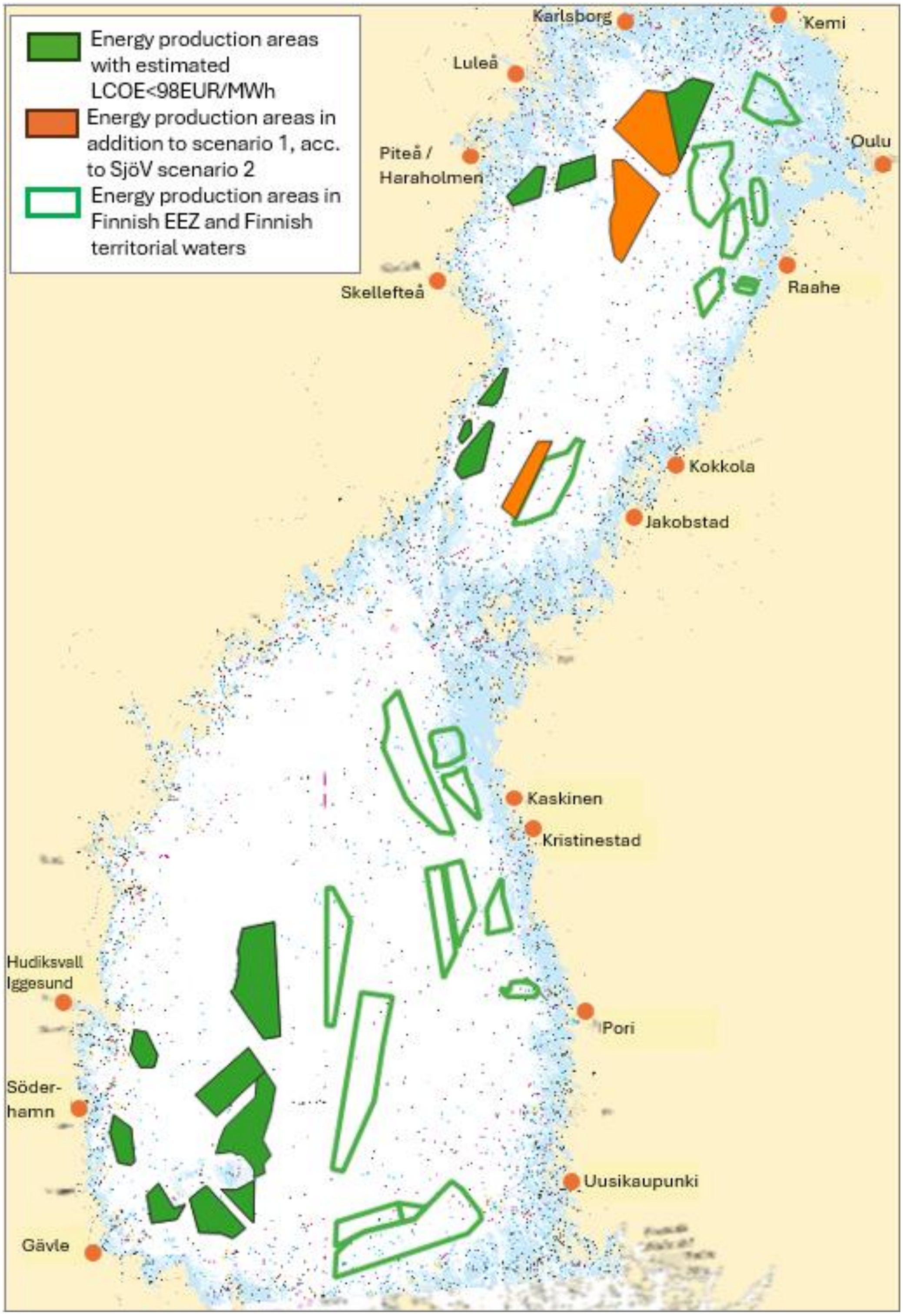

Figure 1 Energy production areas included in the analysis

Route extensions and increased fuel costs have been calculated for the routes to a number of ports, selected together with the Swedish Maritime Administration. The included ports in the Bothnian Sea are Gävle, Söderhamn and Iggesund/Hudiksvall, Kaskinen (Kaskö), Kristinestad (Kristiinankaupunki), Pori (Björneborg) and Uusikaupunki (Nystad). The selected ports in the Bay of Bothnia are Skellefteå, Haraholmen/Piteå, Luleå, Karlsborg, Jakobstad (Pietarsaari), Kokkola (Karleby), Raahe (Brahestad), Oulu (Uleåborg) and Kemi.

1.3 Metod

For the Swedish ports included in the analysis, statistics regarding ship calls (during periods when ice-class-based traffic restrictions[5] were in force) are based on the Swedish Maritime Administration's publications *"Summary of the Ice Winters"* (Swedish Maritime Administration, 2025) for the years covered in the analysis. The summary for the winter of 2023/2024 is not publicly available; therefore, data for this season were obtained directly from the Swedish Maritime Administration.

For the Finnish ports included in the analysis, statistics concerning ship calls are based on AIS data for the relevant periods as well as information received from the Finnish Transport Infrastructure Agency, via email and digital meetings during spring 2025.

A ship call corresponds to both an arrival and a departure, meaning that a ship call in terms of distance covers both the approach to the port and the departure from the port.

Both the Swedish and Finnish assistance statistics for icebreakers are based on extracts from IBNet[6], sorted by so-called associated port (port related to specific assistance). The Atle class[7] forms the basis for costs in the analysis, and data regarding speed and average consumption have been obtained from the Swedish Maritime Administration.

The projection of ship traffic to a future traffic scenario for the year 2030 has been carried out based on contact with ports, public information, and forecasts for freight transport from the Swedish Transport Administration.

The routes that vessels choose today vary due to wind direction and ice conditions, but for each wind direction it is nevertheless possible to identify possible or suitable routes. By combining AIS data for current ship traffic with ice maps, example routes have been identified for today's traffic in the Bay of Bothnia, for each wind direction, and these constitute example routes for current traffic. For the Bothnian Sea, wind direction has not been considered.

In the current analysis, four different characteristic ice scenarios have been identified for the Bay of Bothnia, using ice maps from SMHI (SMHI, 2025), for northerly, easterly, southerly and westerly wind directions, see Figure 2.

[5] Ice class-based traffic restriction. The Finnish-Swedish ice class designations are applied to issue restrictions on the minimum ice class a vessel must have to operate in a specific area. The ice class designations (II, 1C, 1B, 1A, and 1A Super) are based on a classification where the ice thickness defines the different categories. 1A Super represents the highest ice class for navigation in extreme ice conditions with an ice thickness greater than 100 centimetres, while ice class II is the lowest, intended for very light ice conditions with an ice thickness of 10–15 centimetres (SMHI, 2021).
[6] IBNet is an IT system developed in collaboration between Sweden and Finland, and is used to manage and plan the icebreaking operations of both countries.
[7] The Atle class refers to the series of icebreakers that, in addition to Atle, also includes Frej, Ymer, as well as the Finnish icebreakers Urho and Sisu.

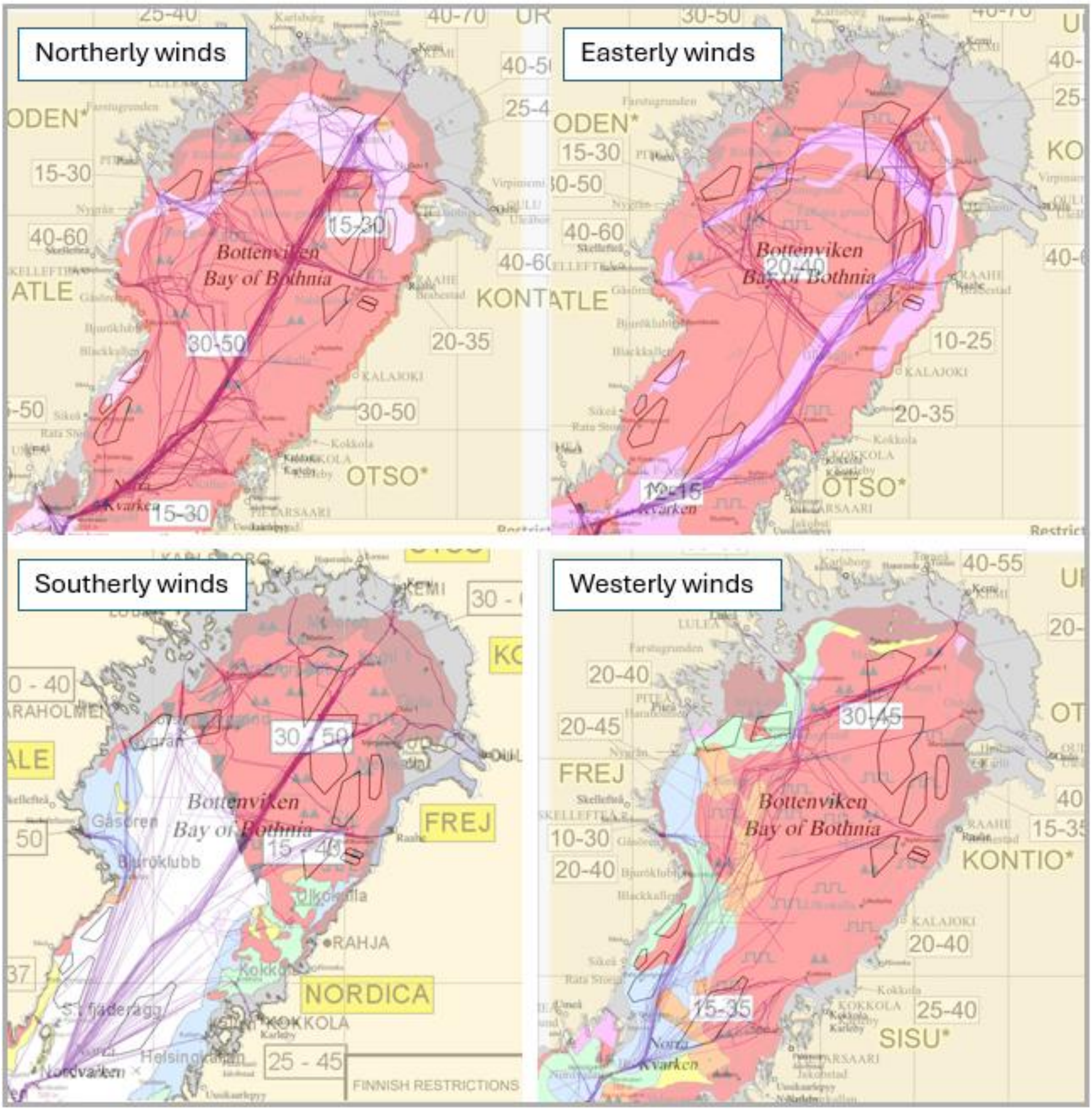

Figure 2: Ice maps depicting characteristic ice conditions under various wind directions, illustrating sample overlay of vessel traffic based on AIS data and wind farms as per Scenario 1.

For the future scenarios, the wind farm areas included in the analysis have been applied as layers onto the ice charts, and new potential example routes have been mapped out, taking into account both the wind farm areas and the ice situation for all wind directions. These new routes were reviewed with senior officers from the Swedish icebreakers during two separate meetings, held on 7 March and 9 May 2025.

Based on wind statistics from SMHI, derived from observations at the Kemi Fyr measuring station covering the period 2015–2025, a distribution of wind directions has been established, as presented in Table 1.

Table 1 Annual distribution of wind direction.

Wind direction:	**Northerly**	**Easterly**	**Southerly**	**Westerly**
Share / year:	22 %	18 %	27 %	33%

Subsequently, based on the distribution of wind directions, the number of commercial vessel voyages and the number of icebreaking assistances on each route have been allocated to each wind direction, since various ice conditions influence route selection and thus the calculation of any route extensions. For each port considered in the analysis, future routes have been compared with current ones to determine any potential increase in route length per route. The analysis incorporates various winter scenarios—mild, average, and severe—each requiring differing levels of icebreaker support, though the report primarily focuses on an average year. Additionally, calculations are presented for a ten-year average, assuming that within a decade there will be one severe winter with high demand for assistance, five average winters with moderate need for ice breaking assistance, and four mild winters with less need for icebreaking assistance. The number of vessels requiring assistance is based on statistical demand for each typical winter, but the distance requiring assistance has been adjusted in line with new example routes reflecting the establishment of wind farms.

2 Description of traffic and routes

The following chapter outlines both current and anticipated patterns of maritime traffic, icebreaking operations, and navigational routes.

2.1 Routes and traffic of today

At present, with no wind farms established in either the Bothnian Sea or the Bay of Bothnia, routes through the sea ice are chosen mainly according to the most navigable path, which depends on the nature of the ice and prevailing weather conditions. Often, a combination of designated guidance routes[8] and icebreaker assistance is utilised. Assistance may involve an icebreaker managing a single vessel, sometimes by towing, or operating in convoy where one icebreaker aids several ships following each other within the broken channel.

The most navigable route in the Bothnian Sea might, for instance, require traffic between Southern Quark and Gävle to take a slightly more northerly course than would be necessary in ice-free waters, or for Sundsvall-bound vessels to follow a more westerly route than usual when sea ice is present.

In the Bothnian Sea, the distances between ports are considerable, so, wherever possible, ships are directed to locations where they can receive assistance or wait without risk of drifting aground. During severe ice winters, when vessels have limited ability to proceed unaided, icebreakers may have to cover long distances in the Bothnian Sea. However, the vast open areas allow ships to drift with the ice, meaning icebreakers can still reach them in time, both in terms of safety, since there is no increased risk for e.g. grounding, and service level, as waiting times are not excessively long. The Swedish Maritime Administration aims to ensure that vessels receive assistance within four hours. Exceptions to the open water in the Bothnian Sea include shallow regions at Storgrundet (about five nautical miles southwest of Ljusne), Finngrundsbankarna (approximately seventeen nautical miles west of Norrsundet), and Vänta Litets Grund (around six nautical miles southwest of Härnösand), as shown in Figure 3.

[8] Designated **routing paths:** Designated routes for maritime traffic, along which vessels can proceed independently to a point where they are met by icebreakers.

Figure 3 The Bothnian Sea and Bay of Bothnia with vessel traffic tracks (AIS data) from December 2023 to April 2024.

In the Bay of Bothnia, the distances between ports are shorter, leaving less space for vessels to drift. The ice situation here differs from that in the Bothnian Sea, as sea ice is present every year. Nevertheless, guided routes are used as much as possible in this region too. It is common for ships to have to wait for assistance in the Bay of Bothnia, with a usual waiting area being between Piteå and Oulu, centrally located in the bay.

Because sea ice is always present, wind strength and direction significantly influence the choice of the most navigable route. Easterly winds often open a lead along the eastern side of the Bay of Bothnia, enabling vessels to travel unaided over a longer distance. In contrast, with westerly winds, ships are more frequently directed or assisted on the western side. Northerly winds typically cause ice to build up around the shallow areas near the Nordvalen lighthouse in the Northern Quark (see Figure 3), so vessels heading for ports in the northeast are centrally assisted within the Bay of Bothnia.

There are certain parts of the Bay of Bothnia where the ice situation can become particularly challenging due to shallow waters, which allow grounded ice ridges to form easily. Areas with particularly harsh conditions include the Northern Quark, as well as the approaches to Kemi and Oulu. The main approach to Luleå via the Sandöleden at Farstugrund can be extremely difficult in winter because of large, solidified areas with very compact ice ridges. As an alternative to the Sandöleden, the Sandgrönnleden can be used, which, depending on wind and ice pressure, may feature natural leads and offer better navigability. Another route sometimes used is the so-called Marakallaleden, which runs between the Sandgrönnleden and Sandöleden (see Figure 4).

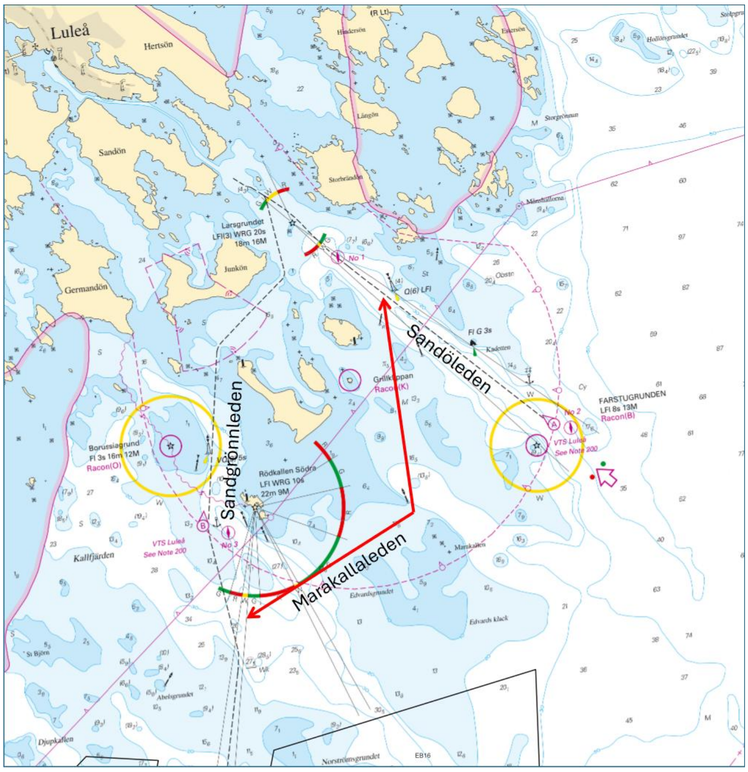

Figure 4: Alternative Approaches to Luleå

A portion of icebreaker operations consists of transit journeys, meaning distances travelled without actively assisting vessels, either en route to ships requiring help or following completed assistance. Based on historical records for Swedish icebreakers over the years analysed, these transit segments currently represent between 35 and 58 percent of total icebreaker activity, with an average of 47 percent.

Presently, Sweden operates six icebreakers: Atle, Frej, Idun, Oden, Ymer, and Ale — the latter specifically designed for Lake Vänern. Finland, meanwhile, can deploy nine icebreakers through partnerships with Alfons Håkans and Arctia: Polaris, Fennica, Nordica, Otso, Kontio, Urho, Sisu, Voima, and Zeus. In particularly cold winters, typically five Finnish icebreakers are stationed in the Bay of Bothnia. In addition, there is a Finnish icebreaker configuration known as “Saima + Calypso”, which comprises the icebreaker Calypso and a detachable, self-propelled icebreaker bow, developed for the Saimaa Canal. This vessel was utilised in the Bothnian Sea during the harsh winter of 2023/2024. The deployment and location of icebreakers naturally depend on ice conditions and operational requirements. During the peak extent of sea ice in the winter of 2023/2024, a total of twelve icebreakers were present in the Bothnian Sea and Bay of Bothnia.

2.2 Future traffic

According to the Swedish Transport Administration’s baseline forecast for 2023 (Trafikverket, 2023), annual growth in shipping between 2017 and 2040 is predicted at +1.7% per year. However, an updated forecast in 2024, extending to 2045, suggests that freight transport in Sweden will increase at a much slower pace than previously anticipated, aligning more closely with historical trends. This revision is primarily attributed by Trafikverket (Trafikverket, 2024) to the following factors:

- Slower economic growth,
- The value of goods is expected to rise, thereby dampening the corresponding increase in tonnage,
- The use of crude oil and petroleum products in the transport sector is anticipated to all but cease due to climate policy measures.

The 2024 forecast indicates that shipping activity will stagnate, with a predicted annual decline of -0.6%. This is largely due to a significant reduction in the transport of crude oil and petroleum products, as road traffic transitions from fuel-based to electric vehicles. However, the forecast also notes that if electrification proceeds only half as quickly as assumed in the baseline scenario, freight volumes in the shipping sector could instead increase considerably. In such a case, rather than a 13% decrease between 2019 and 2045, there would be a 5% increase over the same period.

It remains uncertain whether any potential increase in freight traffic would be handled by larger ships or simply by a greater number of vessels. Therefore, additional data has been gathered from port forecasts, whereas most ports predict a 2% annual rise in vessel calls. For this analysis, it is assumed that, for most ports, the number of ship calls will rise by 10% from today’s levels by 2030, with a few exceptions:

- Luleå Port: The forecasted increase by 2030 is a fourfold rise in traffic, owing to major ongoing projects related to the steel industry (Luleå Hamn, 2024).
- Kokkola: Traffic is expected to grow by approximately 25% by 2030 (Karleby Hamn, 2025).
- Pietarsaari: Traffic is predicted to increase by about 30% by 2030 (Jakobstad Hamn, 2024).

The actual numerical increase in ship calls is relatively small for Kokkola and Pietarsaari, an additional of 150 and 100 ships respectively, resulting in an expected vessel movement of 750 and 400 vessel per year by 2030. In contrast, the rise for Luleå is significant: from around 600 ships per year currently to an anticipated 2,500 by 2030. This surge in traffic to Luleå has a pronounced impact on subsequent calculations and greatly affects the need for ice breaking assistance, even without the development of offshore wind power.

The average increase in traffic across all ports is estimated at 27%.

The same increase factor has been applied to all typical winter scenarios in the analysis. The calculations do not compensate for the fact that, for example, traffic in 2010/2011 was less intensive than in 2023/2024. The winter of 2010/2011 was the most recent severe ice season, and the analysis assumed that the proportion of icebreaking assistances to total vessel passages in a future severe winter would be the same. While traffic may fluctuate somewhat during a harsh winter, an average increase of 27 %, on the traffic during a typical winter such as 2023/2024, may also be an overestimation of the shipping volume year 2030.

2.3 Future routes

In a future where offshore wind farms are situated in the relevant areas, their impact on maritime traffic will depend on the precise locations of these wind farms. Should current shipping routes pass through the proposed wind farm areas, vessels will need to be rerouted, considering that such diversions would be influenced by factors such as water depth and the extent of navigable waters available. Additionally, wind conditions can affect how ice forms or breaks up in different sectors, meaning some regions will present greater challenges for navigation than others, depending on the prevailing circumstances.

2.3.1 Bay of Bothnia

Sea ice occurs in the Bay of Bothnia every year, persisting from a few months to the entire winter season, and requires icebreaking operations annually. The wind farm areas considered in the analysis, both for scenario 1 and 2, are situated just north of Northern Quark and along the northern and northeastern coastline of the Bay of Bothnia.

To estimate potential future shipping routes following the development of wind farms under both scenarios, various wind and ice conditions in the Bay of Bothnia have been examined. The wind direction directly influences ice formation and movement, and currently, without wind farms, icebreakers and vessels are free to select the most navigable paths. The passage through Nordvalen and the Northern Quark exemplify a critical area, especially when northerly winds compress ice towards the shallow regions surrounding the Northern Quark.

The introduction of wind farms in such locations could force vessels onto routes through thicker, more challenging ice, or even restrict access to certain ports either partially or entirely. Figure 5 displays ice maps sourced from the Swedish Meteorological and Hydrological Institute (SMHI), illustrating how ice conditions in the Bay of Bothnia vary according to different wind directions, north, east, south, and west, with Figure 6 providing a key to interpreting these maps.

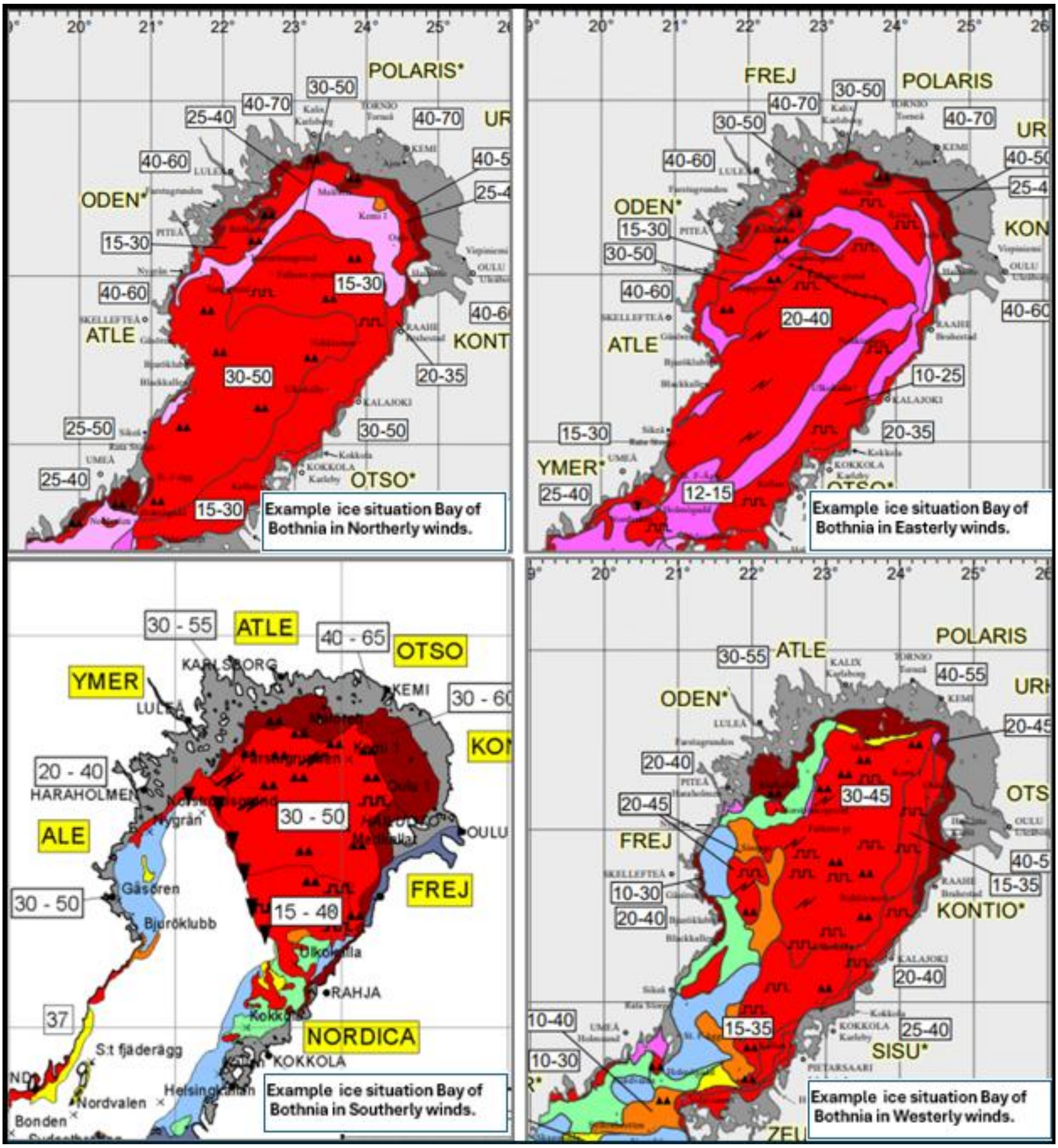

Figure 5: Examples of typical ice conditions under Northerly, Easterly, Southerly, and Westerly winds

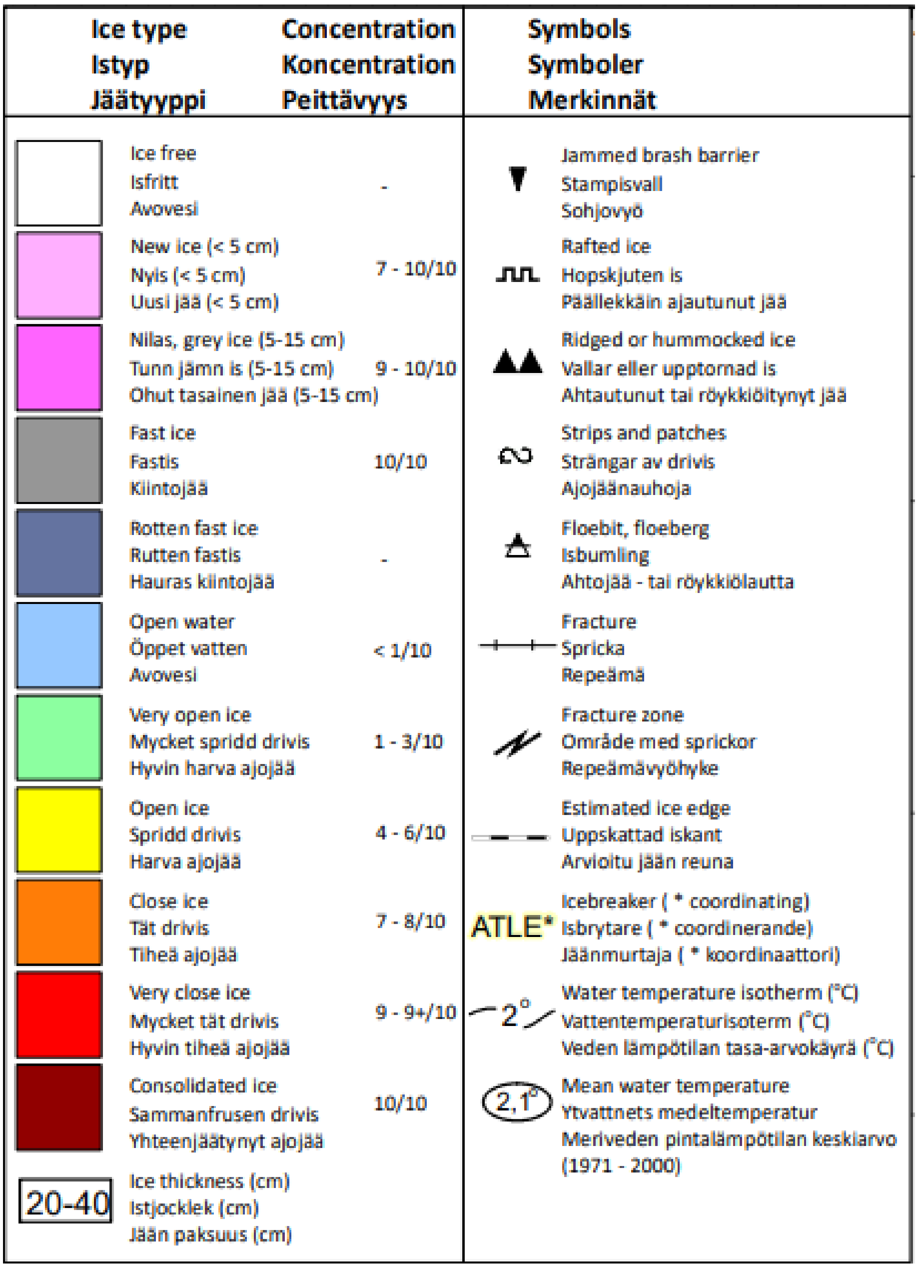

Figure 6 Legend for ice maps in Figures 2, 4, 5, and 6. (SMHI, 2025) For Figures 4 to 6, where ice maps are superimposed onto nautical charts with AIS data, the colors appear more matted but are still interpretable using the color scale.

In Figure 7 below, a selection of AIS data has been overlaid onto the ice maps to illustrate current shipping routes; additionally, energy production areas, as per scenario 1, are shown as outlines. The figure demonstrates that alternative routes will need to be chosen if certain areas are developed, and also that safe passage to ports such as Kemi and Oulu will not be possible in the event of full development of all energy production areas in north-eastern Bay of Bothnia. In the southern Bay of Bothnia, just north of the Northern Quark, passage east of the energy production areas is associated with considerable risks due to the narrow distance between them and shallow areas. New proposed example routes, reviewed by icebreaker captains for different wind directions and ice conditions, are shown in the figure as dashed lines. Where the lines are marked red, a reduction in the extent of energy areas is required to allow vessel traffic to pass safely.

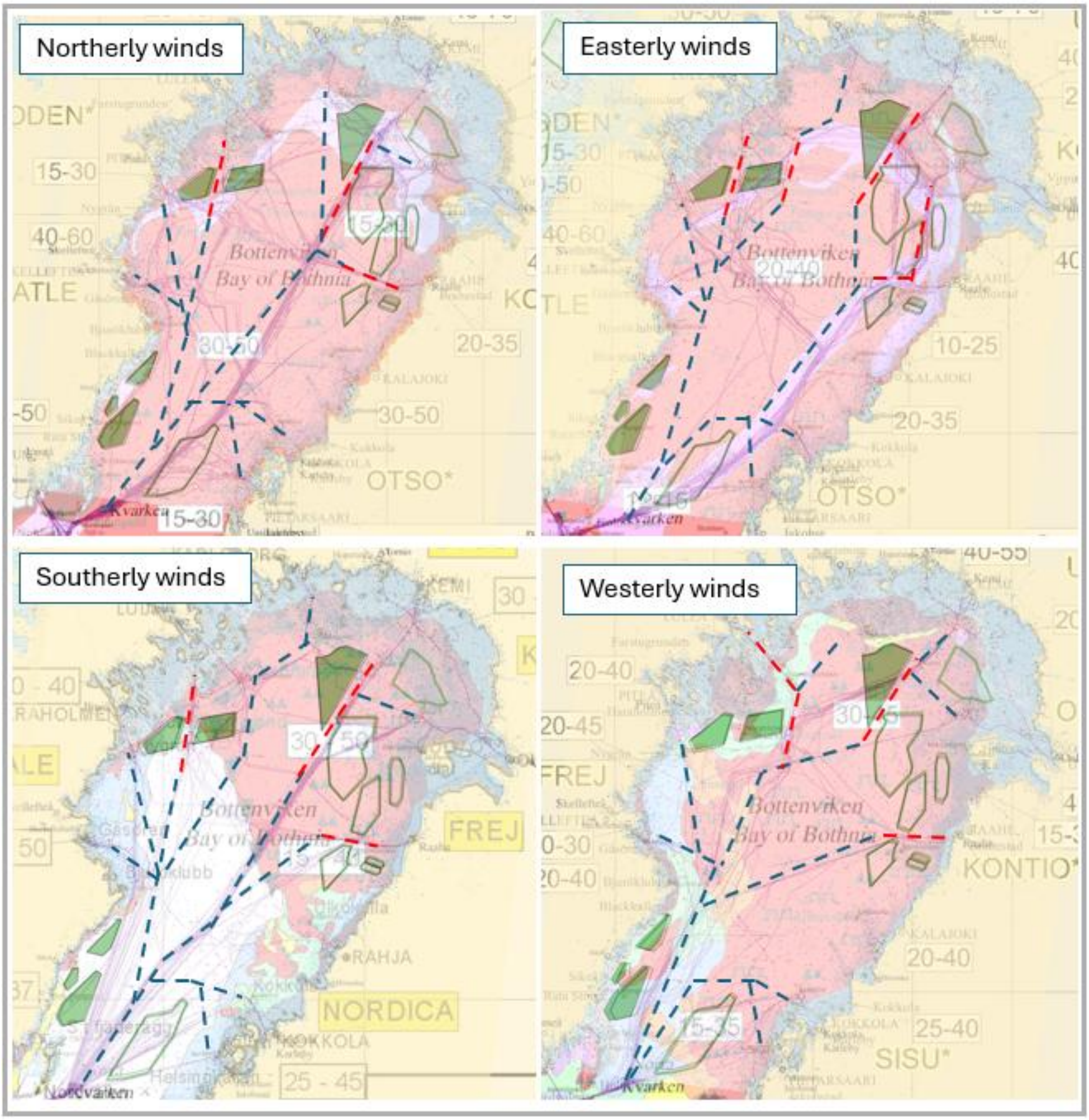

Figure 7 presents ice maps overlaid with example shipping traffic data for relevant wind directions (AIS data), alongside the proposed establishment of wind farms in accordance with energy production areas under scenario 1. Newly suggested routes are indicated by dashed lines. Energy areas with a green border are located in the Finnish Exclusive Economic Zone (EEZ) or Finnish territorial waters, while solid green areas are within Swedish waters.

If development proceeds according to scenario 2, which introduces energy productions areas in the areas highlighted in orange, the available space for alternative shipping routes becomes even more restricted in the northern parts and just north of the Northern Quark, see Figure 8. Access to ports north of Piteå on the western side, and to Brahestad on the eastern side of the Bay of Bothnia, would no longer be possible if the northern energy areas are fully established. In the southern Bay of Bothnia, the situation mirrors that of scenario 1: navigating east of the energy areas just north of the Northern Quark is considered highly risky due to the narrow gap between the wind farm zones and shallow waters. Under scenario 2, an additional energy area is positioned adjacent to the easternmost zone just north of Nordvalen, which further reduces navigable waters on the western side of these areas, leaving a distance of approximately 9 nautical miles to the next wind farm further west.

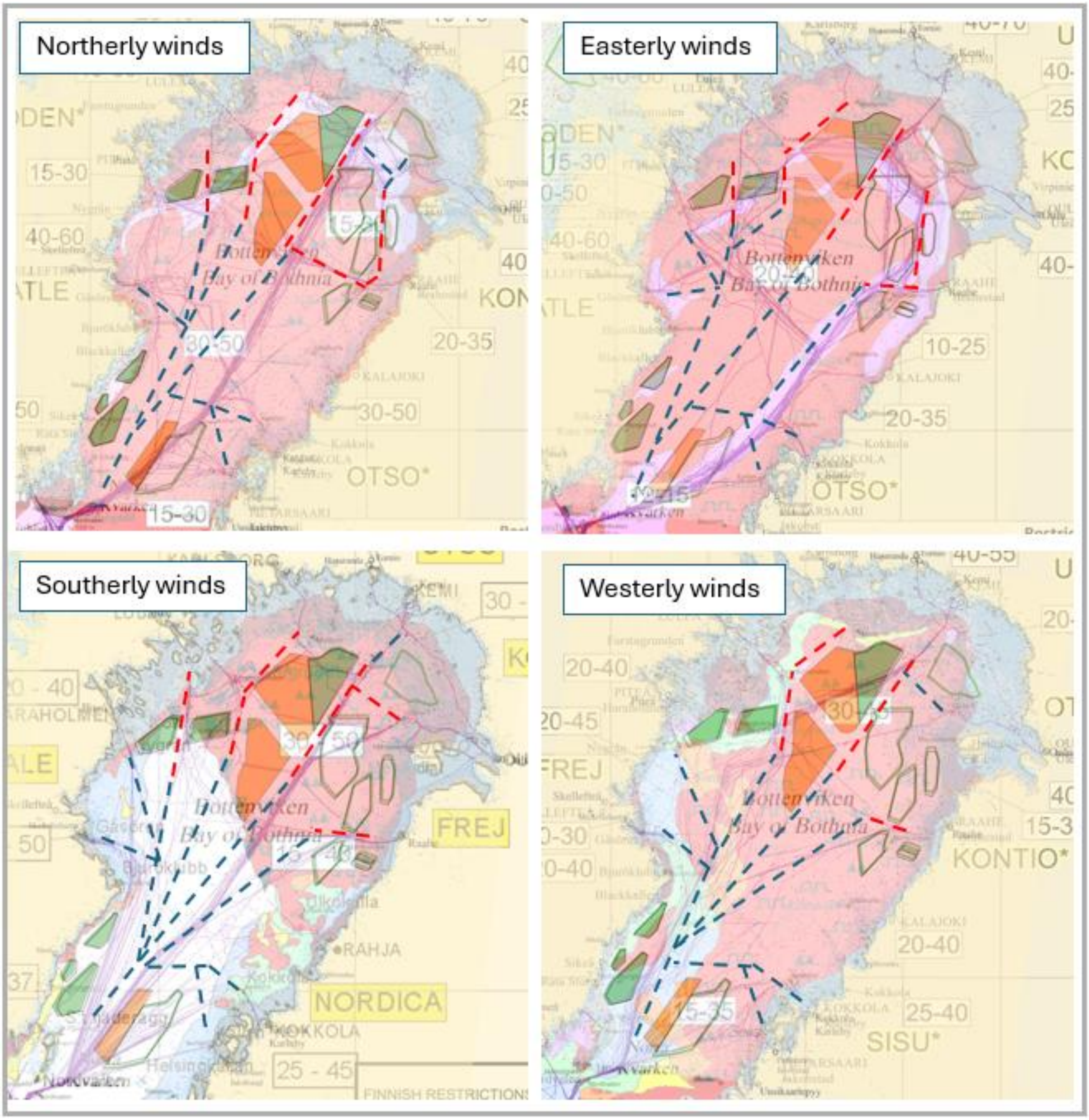

Figure 8 presents ice charts for example scenarios under differing wind directions, incorporating the establishment of wind farms as outlined in scenario 2, with the newly added areas highlighted in orange. Energy zones bordered in green are located within the Finnish Exclusive Economic Zone (EEZ) or Finnish territorial waters, while the fully green areas denote Swedish waters. Overlaid vessel traffic, shown as purple lines (AIS data), highlights current navigation patterns. Newly proposed routes are depicted as dashed lines; where these lines are marked in red, a reduction in the size of the energy zones is necessary to ensure maritime traffic can pass through safely.

There are currently no established guidelines regarding the minimum distance between two adjacent wind farms. The UK Maritime and Coastguard Agency (MCA), in MGN 654, provides recommendations for corridor widths in ice-free waters, allowing for a 20° drift over the length of the corridor (Maritime & Coastguard Agency, 2021). For example, this equates to a width of approximately 3.6 nautical miles for a corridor 10 nautical miles in length. However, these MCA recommendations do not directly apply in the presence of sea ice, as they do not account for ice drift; instead, they merely indicate a minimum width to enable vessels to navigate safely through a corridor without drifting into the wind farm.

The Finnish Transport Infrastructure Agency has suggested that a distance of 6 nautical miles between wind farms serves as a guideline from a risk perspective, and potentially a greater distance may be necessary when sea ice is present. Within their own EEZ or territorial waters, each country may recommend a suitable corridor width but establishing wind farms close to the EEZ boundary is more complex. Nevertheless, in line with a minimum corridor of 6 nautical miles, the Finnish authority has indicated that Finnish wind farms could be situated as close as 3 nautical miles from the border, provided that wind farms on Swedish waters or within the Swedish EEZ adhere to the same principle. This, however, does not represent an official position of the Swedish maritime authorities. To illustrate the impact in northern Bay of Bothnia of applying 6-nautical mile corridors between adjacent energy areas, theoretical blocks representing such spaces are shown in Figure 9. Imposing such a limitation on the foundation areas would particularly affect the southeastern areas, where the energy areas would be substantially reduced.

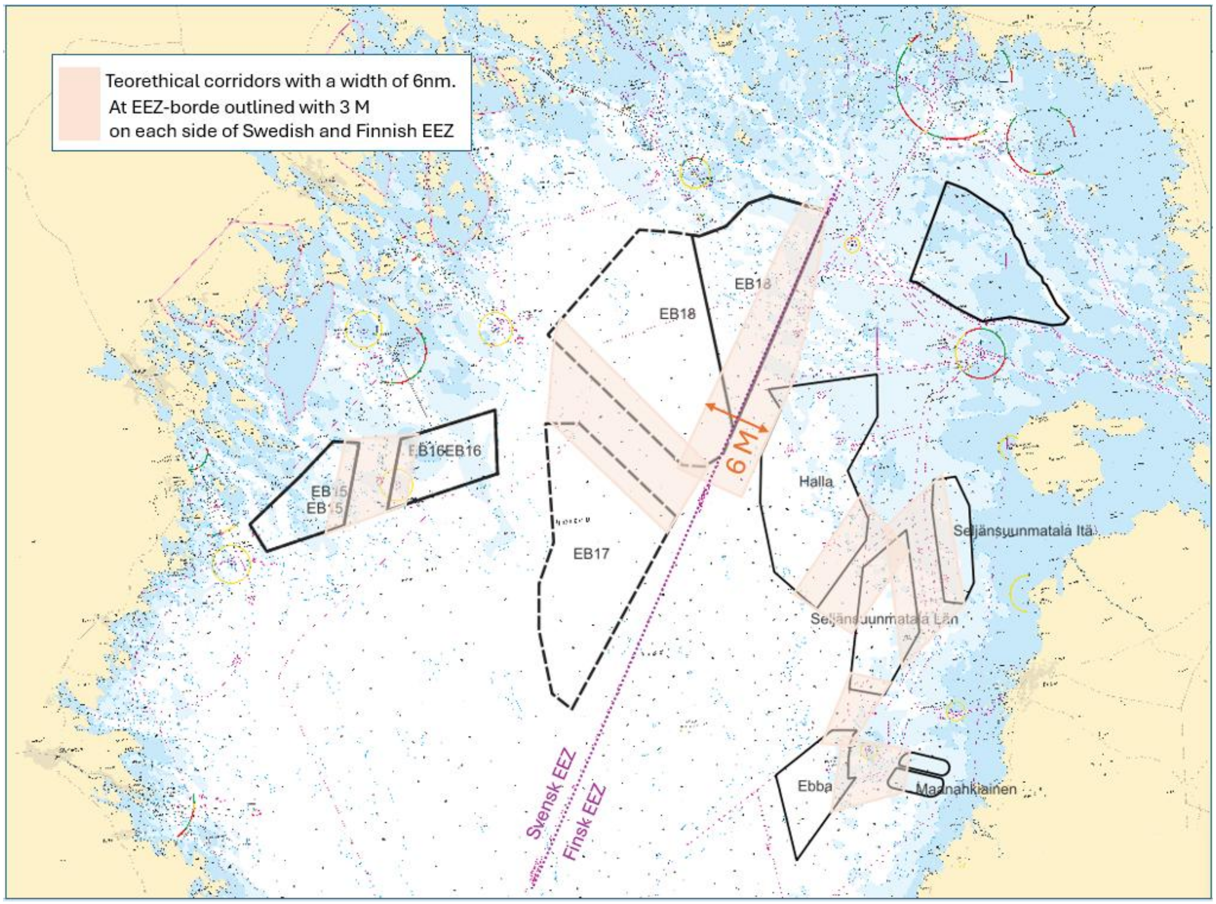

Figure 9 Energy zones in the northern Bay of Bothnia with theoretical corridors between adjacent areas.

In conditions where sea ice is present, both Swedish and Finnish maritime authorities agree that icebreaker assistance is essential for vessels navigating through a corridor. Should a vessel attempt passage without such support and subsequently become trapped and drift sideways with the ice, there is a significant risk that it could drift into a wind farm. Assuming a corridor width of 6 nautical miles, assistance would be required within roughly two hours if the ice drift speed is between 1.5 and 2 knots. In practice, this means that icebreaker escort through the corridor is necessary unless an icebreaker can be on site within about 1.5 hours.

2.3.2 Bothnian Sea

In the Bothnian Sea, the conditions concerning sea ice differ from those elsewhere. In the southern section, where most energy production areas on the Swedish side are situated, severe ice conditions are uncommon, and during a typical winter sea ice generally forms only along the coast and around Finngrundet. However, the southwestern part of Gävlebukten can become particularly challenging to navigate during northerly winds, as ice tends to accumulate between Öregrund and Gävle. When such situations arise, winter navigation routes must be diverted somewhat further north before vessels can resume their course southwest towards Gävle.

The assessment for the Bothnian Sea considers potential future shipping routes based on the maximum extent of ice during a standard winter, with Figure 10 illustrating the greatest ice coverage observed in the winter of 2023–2024.

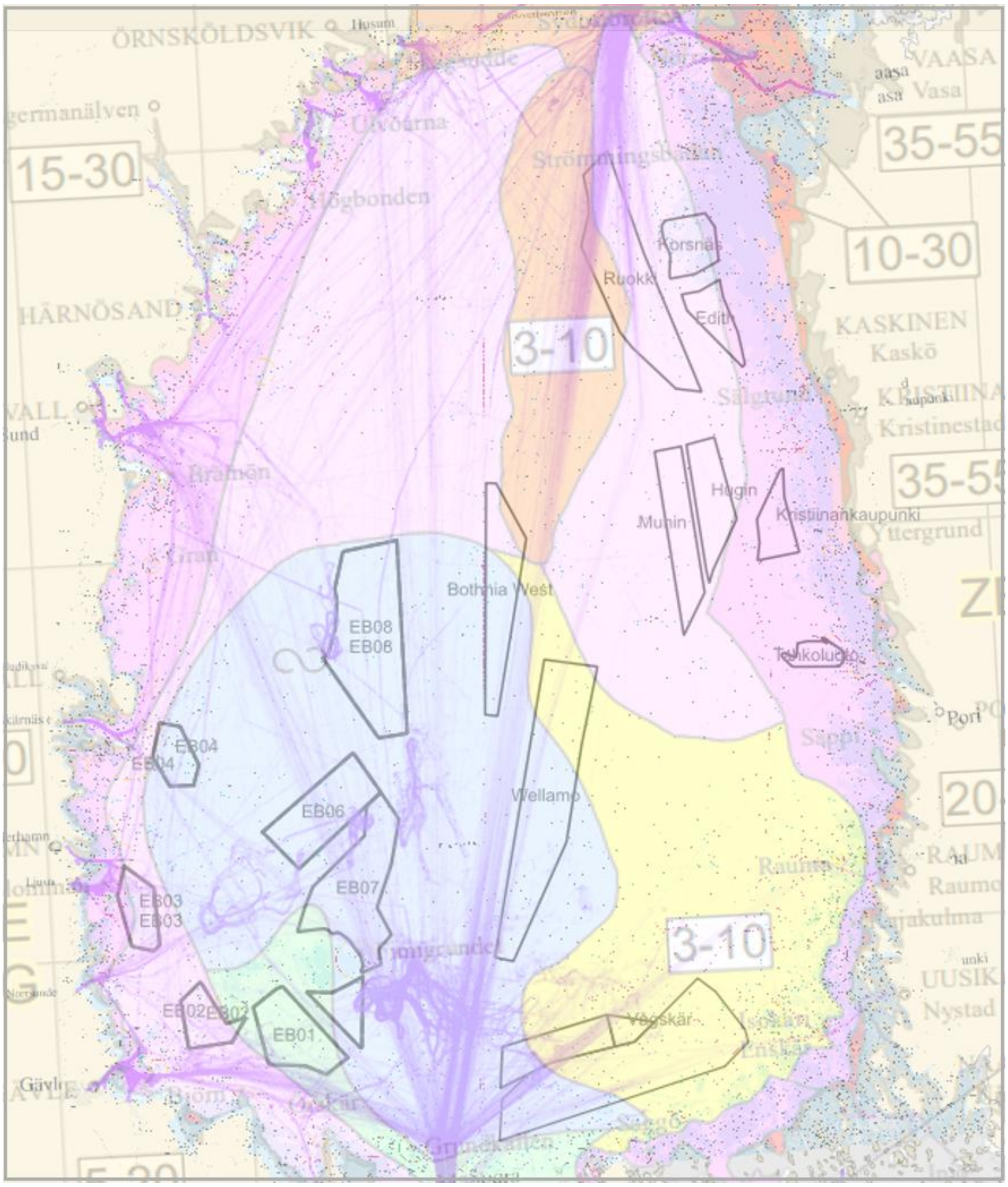

Figure 10 illustrates the maximum extent of ice observed during a typical winter in 2023–2024, with an ice chart superimposed onto a nautical chart displaying AIS shipping data from January to April 2024.

If wind farms are constructed in locations that coincide with current icebreaker assistance routes south of Finngrundet, a new assistance route will need to be established to the north of Finngrundet and the planned energy production areas, particularly for shipping bound for ports such as Gävle, Söderhamn, and Iggesund, ref. Figure 11. Within the Finnish Exclusive Economic Zone (EEZ) and Finnish territorial waters, wind farms are primarily planned in the central Bothnian Sea and along the northeastern section, with the exception of an area just north of the Southern Quark. Potential alternative routes to ports like Uusikaupunki (Nystad), and Pori (Björneborg) are also illustrated in Figure 11.

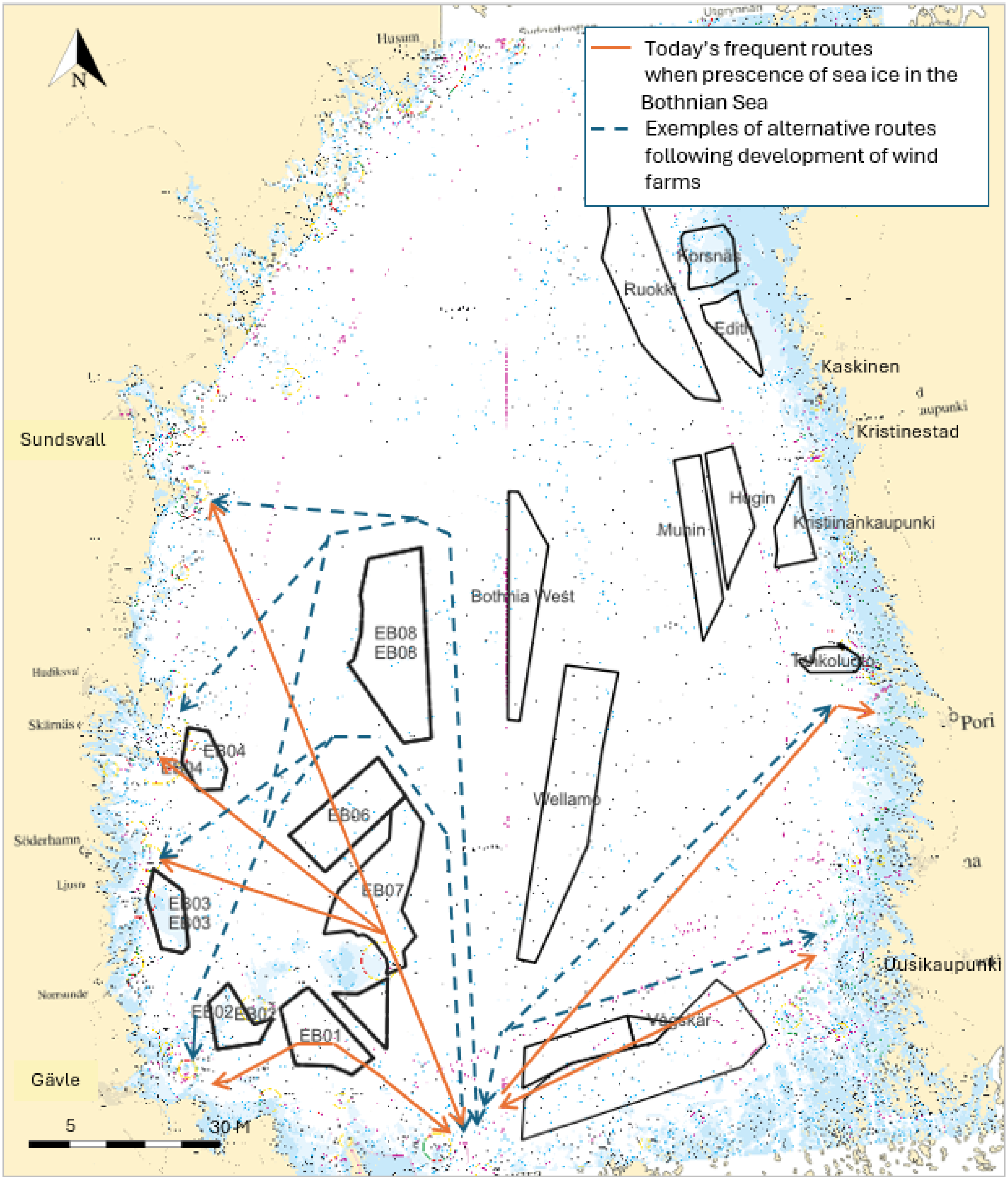

Figure 11: The orange route highlights a current icebreaker assistance path in the south-western Bothnian Sea during icy conditions, while the blue dashed lines depict example routes that may be required if wind farms are established.

Shipping traffic from the Southern Quark to Finnish ports located slightly further north, such as Kaskinen (Kaskö) and Kristinestad, is minimal and therefore excluded from this analysis.

2.4 Estimation of route extensions and increase in assistance distances

Based on new potential example routes, which have been coordinated with senior icebreaker officers, the increase in route distances for commercial vessels has been calculated. For the Bay of Bothnia, the calculations take into account ice conditions influenced by wind direction, as wind plays a significant role in how the ice forms and moves. In the Bay of Bothnia, this has a particularly large impact on the possible navigable routes for vessels and on the need for icebreaker assistance. In the Bothnian Sea, route extensions and assistance requirements are calculated independently of wind, as sea ice is much less prevalent here than in the Bay of Bothnia. Consequently, the frequency of different wind directions in the Bothnian Sea is not considered to have a significant impact on routes and assistance and is therefore not deemed relevant to the overall analysis.

The number of vessel calls at Swedish ports is based on statistics from the Swedish Maritime Administration's Winter navigation publication for the years included in the analysis. For Finnish ports, statistics have been obtained from both the Finnish Transport Infrastructure Agency and AIS data for the relevant years. The number of icebreaking assistance operations is based on extracts from IBNet. The predicted traffic for 2030 has been scaled up according to Chapter 2.2 and is referred to as the "number of vessel passages in 2030" in Table 2.

Future assistance distances for icebreakers have also been calculated, based on the example routes in the analysis. This includes a zero scenario for 2030, meaning predicted traffic growth without any wind farms established, as well as scenarios 1 and 2 with wind farms in accordance with energy production areas. The calculations consider the need for assistance according to ice conditions; for instance, more vessels require assistance during a severe ice winter than during a mild one. A severe ice winter with high demand for assistance is assumed to occur once every ten years (as in the winter of 2010/2011 in the analysis), a normal winter with moderate assistance demand is assumed to occur five times in ten years (winters 2017/2018 and 2023/2024 in the analysis), and a mild winter with low assistance demand is expected four times in ten years (winter 2019/2020 in the analysis). In a future scenario where wind farms are built in areas with sea ice, it is assumed that all vessels currently requiring assistance will need to be escorted over longer distances whenever sea ice is present, as the assistance will have to pass the wind farms, thereby increasing the distance icebreakers need to travel.

Some of the icebreakers' work will continue to consist of transit operations. In this analysis, an average of 50% is assumed for transit journeys in relation to the icebreakers' total operational distance, based on the current average of 47% for Swedish icebreakers. However, it is likely that a different operational pattern will be required for icebreakers in the future, and the share of transit operations is therefore uncertain. Additionally, current transit data for Finnish icebreakers could not be verified.

2.4.1 Bay of Bothnia

With the introduction of new example routes that take energy areas into account, as shown in Figure 5 in Section 2.3.1, the total additional distance for all commercial vessels, including predicted traffic growth up to 2030, would be approximately 11,500 nautical miles in Scenario 1 for a winter with an average demand for icebreaking assistance (based on the normal ice winters analysed). In Scenario 2, the total distance increase for commercial vessels for an average winter with medium assistance needs would be about 21,800 nautical miles.

On average, over a ten-year period, the increase in distance that commercial vessels must travel is estimated at around 7,800 nautical miles for Scenario 1 and about 16,000 nautical miles for Scenario 2.

The table below (Table 2) presents the altered distances and total increased icebreaker assistance distance in 2030 for both commercial vessels and icebreakers, averaged over ten years (considering winters with high, medium, and low assistance demands). Traffic growth alone significantly raises the demand for icebreaker assistance compared to current levels. The establishment of wind farms in the energy areas considered in the analysis would further increase the required assistance distance: compared to Scenario 0 in 2030 (i.e., 2030 considering only traffic growth), the assistance distance would rise by 36 % with wind farm development as per Scenario 1. For Scenario 2, the increase in assistance distance would amount to 43 % relative to Scenario 0.

Table 2 Distances and Assistance Distances for the Bay of Bothnia, Averaged Over Ten Years.

Route	Bay of Bothnia - 10 year average							
	Number of ship passages år 2030	Distance (nm), scenario 0 2030 (without energy production areas)	Increased distance (nm), scenario 1	Increased distance (nm), scenario 2	Number of assistances	Assistance distance (nm), scenario 0 2030 (without energy production areas)	Increased assistance distance (nm), with energy production areas acc to scenario 1	Increased assistance distance (nm), with energy production areas acc to scenario 2
Norra Kvarken-Skellefteå	410	31 813	-729	-1 173	110	3 152	2 826	2 631
Norra Kvarken-Piteå/Haraholmen	567	57 019	-615	-615	148	4 533	3 371	3 502
Norra Kvarken-Luleå	2 523	333 538	5 473	5 473	1 157	80 667	38 843	42 960
Norra Kvarken – Karlsborg	181	28 110	-644	-161	83	8 685	1 186	1 742
Norra Kvarken-Kemi/Torneå	1 354	205 407	733	4 097	891	94 091	16 568	24 398
Norra Kvarken-Uleåborg	477	66 074	2 390	3 423	315	26 304	12 180	15 109
Norra Kvarken-Brahestad	245	27 703	0	331	191	10 543	5 562	5 562
Norra Kvarken-Karleby	256	16 195	1 202	3 213	57	2 034	1 093	1 467
Norra Kvarken-Jakobstad	201	7 921	0	1 310	99	2 113	851	1 496
Kemi – Skellefteå	56	0	0	0	21	0	0	0
Luleå – Brahestad	492	0	0	0	224	0	0	0
TOTALT	6 761	773 781	7 810	15 899	3 296	232 122	82 480	98 867
						Added increase due to energy production areas:	36%	43%

Historical data from IBNet, supplied by the Swedish Maritime Administration, indicates that the total distance covered by Swedish and Finnish icebreakers during the years included in the analysis is shown in Table 3. However, it has not been possible to exclude the distances travelled by Finnish state icebreakers in the Gulf of Finland for the years 2010/2011, 2017/2018, and 2019/2020, which means the figures presented below are somewhat overestimated. For 2023/2024, additional data were provided by the Finnish Transport Infrastructure Agency, and the total assistance distance reported for 2023/2024 applies solely to the Bay of Bothnia.

Table 3 Assistance Distances According to Statistics from IBNet for the Years Included in the Analysis (Swedish Maritime Administration, 2025).

Total assistance distance					
Year	2010/2011 (incl Guld of Finland)	2017/2018 (incl Gulf of Finland)	2019/2020 (incl Gulf of Finland)	2023/2024	10-year average
Distance	239 606	118 618	90751	136 057	124 000

An estimated ten-year average assistance distance based on historical IBNet data, using a distribution of one severe, five normal, and four mild ice winters, is approximately 124,000 nautical miles. The average for normal winters is about 128,000 nautical miles. The ten-year average for the calculated assistance distance based on example routes, using today's traffic levels, is approximately 133,000 nautical miles. This means that the example routes slightly overestimate the total distance compared with historically logged assistance distances. However, the percentage increase in assistance from today's example routes to future example routes is still relevant and corresponds to about 74 % for scenario 0 over the ten-year average.

Based on the assumed proportion of transit distance, an increase in assistance distance of 82,000 nautical miles implies an equally large increase in transit distance. This means that the additional operational distance for the icebreakers over a ten-year average will be approximately 164,000 nautical miles due to the establishment of wind power in the energy production areas used in the analysis

2.4.2 Bothnian Sea

With the introduction of new shipping routes that consider the designated energy areas, as shown in Figure 11 of Chapter 2.3.2, the total increased distance for all commercial vessels, including predicted traffic growth up to 2030, is estimated to be roughly 81,000 nautical miles for scenario 1, based on an average winter with moderate assistance requirements. Over a ten-year period, the average increase in distance that commercial vessels must travel is calculated to be approximately 48,000 nautical miles, considering energy areas as specified in scenario 1 and accounting for anticipated traffic growth by 2030.

The icebreaker assistance distance is expected to rise by about 1,600 nautical miles during a typical winter with moderate needs, and the ten-year average increase is estimated at around 800 nautical miles.

Data on the proportion of transit relative to total operational time has been obtained for Swedish icebreakers. During the 2023/2024 winter, Brage Viking and Atle operated in the Swedish section of the Bothnian Sea, while Calypso and Zeus worked on the Finnish side. Transit journeys accounted for approximately 30% of the total operational time for the Swedish icebreakers. As transit data for the Finnish icebreakers is unavailable, it is assumed that transit routes make up half of the total increased distance. Hence, an increase of 1,600 nautical miles in assistance distance for a standard winter with moderate needs would result in an equivalent additional transit distance, bringing the total increased operational distance to 3,200 nautical miles for such a winter. Over a ten-year average, the total increased operational distance would be 1,600 nautical miles.

In the Bothnian Sea, commercial vessels are affected significantly more than icebreakers, as the need for assistance is substantially lower compared to the Bay of Bothnia. Table 4 presents the total estimated increase in distance for commercial vessels and the additional calculated assistance distance for icebreakers, averaged over ten years and encompassing winters with high, moderate, and low assistance needs.

Table 4 Distances and assistance distances for the Bothnian Sea, averaged over a ten-year period.

	Bothnian Sea - 10 year average					
Route	Number of ship passages år 2030	Distance (nm) scenario 0 (without energy production areas)	Increased total distance (nm) scenario 1	Number of assistances 2030	Assistance distance (nm), scenario 0 2030 (without energy production areas)	Increased assistance distance (nm), scenario 1
Södra Kvarken – Gävle	454	20 450	36 356	14	425	-111
Södra Kvarken – Söderhamn	63	4 744	0	2	11	1
Södra Kvarken – Iggesund/Orrskär	234	18 691	4 673	5	27	1
Södra Kvarken – Sundsvall	328	0	0	22	0	0
Södra Kvarken – Örnsköldsvik	261	0	0	30	0	0
Södra Kvarken – Kaskö	256	17 910	5 117	57	4 019	757
Södra Kvarken – Pori	269	20 166	1 344	35	352	1
Södra Kvarken – Nystad	306	16 844	0	19	0	0
	0	0	0	0	0	0
Norra Kvarken – Kaskö	10	724	207	10	673	164
TOTAL	2 181	99 529	47 697	195	5 508	812
					Ytterligare ökning av distans pga vindkraftparker:	15 %

3 Costs and emissions

Calculations relating to fuel consumption and emissions for commercial vessels are based on MRV data[9]. These calculations have been performed using a representative fleet, where the average fuel consumption and emissions are determined for the total vessel traffic (according to AIS data) operating in the Bothnian Sea and Bay of Bothnia, based on the proportion of vessels from relevant categories in each area.

The fuel consumption for icebreakers has been set at 3.5 metric tonnes per hour at 9 knots, as agreed with the Swedish Maritime Administration. CO_2 emissions are set at 3.205 tonnes of CO_2 per tonne of MGO (or MDO), in line with ICCT (2021).

Bunker prices fluctuate with the global market, but at the time of the fuel cost calculation in June 2025, the spot price (Rotterdam basis) for MDO/MGO E10 was EUR 650 per metric tonne, corresponding to SEK 7,150 per metric tonne at the prevailing exchange rate. Icebreakers acquire bunker fuel differently from commercial vessels. The latter buy bunker on the spot market, which may result in a higher average bunker price compared to icebreakers, whose fuel is purchased in larger quantities and stored in tanks from which they bunker as needed. However, for calculation purposes, the same bunker price is used for both commercial vessels and icebreakers.

Bunker costs are likely to rise for the Swedish Maritime Administration. In 2025, a decision was made that the Swedish Maritime Administration fleet should be fossil-free by 2045, in line with Sweden's climate goals. This will likely entail a switch to alternative fuels, for example HVO, which currently costs twice as much as the gas oil used by icebreakers. If HVO maintains this price level in the future, switching to it would significantly increase bunker costs for icebreakers. Moreover, the 2045 target year does not mean the transition will be delayed until then; it may happen sooner. Tests with HVO100 are already underway, and the new icebreaker currently on order is required to be capable of running on alternative fuels and will be delivered 'methanol ready' (Swedish Maritime Administration, 2025).

Nevertheless, the calculations in this analysis are based on current price levels, as the analysis applies to 2030. Should all icebreakers switch to fossil-free fuels by then, it is estimated that their fuel costs would double. The impact on CO_2 emissions when shifting to fossil-free fuels will depend on the specific fuel chosen and its source.

[9] MRV data: Data collected for ships under the EU Regulation on Monitoring, Reporting, and Verification, which requires vessels over 5,000 gross tonnes calling at EU ports to report, among other things, their fuel consumption, carbon dioxide emissions, and distance sailed.

3.1 Bay of Bothnia

For the Bay of Bothnia, the average fuel consumption and CO_2 emissions for representative vessel traffic are presented in Table 5.

Table 5 Fuel Consumption and CO_2 Emissions for Commercial Vessels in the Bay of Bothnia

Traffic Bay of Bothnia (Not including ship type *other*[10] and ice breakers)	**Fuel consumption (kg/M)**	**Fuel consumption (MT/M)**	**CO_2-emissions (kg CO_2/M)**	**CO_2-emissions (MT CO_2/M)**
Average for representative fleet	48,76	0,049	155,02	0,16

For merchant vessels, the distance travelled in the Bay of Bothnia increases by approximately 7,800 nautical miles on average over ten years. Icebreakers, which are significantly more affected in the Bay of Bothnia than merchant ships, will have an assistance distance increase by about 82,000 nautical miles over the same period. This leads to an increase in both fuel consumption and CO_2 emissions, as detailed in Table 6.

Table 6 Increase in fuel consumption, fuel costs and CO_2 emissions for merchant vessels in the Bay of Bothnia, as an average over ten years.

Scenario	**Distance increase commercial shipping (nm)**	**Increased fuel consumption (MT)**	**Increased fuel costs, SEK (MSEK)**	**Increased CO_2-emissions (MT CO_2)**
1	7 810	381	2,7	1 211
2	15 899	779	5,6	2 465

For icebreakers, the total annual increase is as shown in Table 7.

Table 7 Increase in fuel consumption and CO_2 for icebreakers in the Bay of Bothnia, as an average over ten years.

Scenario	**Increased assistance distance ice breakers (nm)**	**Increased fuel consumption (MT) based on 3,5 MT/h at 9 knots**	**Increased fuel costs, SEK (MSEK)**	**Increased CO_2-emissions (MT CO_2)**
1	82 480	32 076	229,3	102 802
2	98 867	38 448	274,9	123 556

[10] AIS-data labels ship types categories, i.e. general cargo, container, tanker, bulk etc. There is also a category named *"other"* which includes e.g. smaller working vessel.

3.2 Bothnian Sea

For the Bay of Bothnia, the average values for fuel consumption and CO_2 emissions for representative vessel traffic are provided in Table 8.

Table 8: Fuel Consumption and CO_2 Emissions for Merchant Vessels in the Bay of Bothnia

Traffic Bothnian Sea **(Not including ship type "*other*" and ice breakers)**	**Fuel consumption** **(kg/M)**	**Fuel consumption** **(MT/M)**	**CO_2-emissions** **(kg CO_2/M)**	**CO_2-emissions** **(MT CO_2/M)**
Average for representative fleet	53,44	0,053	169,55	0,17

For merchant vessels, the distance sailed in the Bothnian Sea increases by approximately 48,000 nautical miles on average over ten years. In the Bothnian Sea, icebreakers are less affected than merchant vessels by wind farm-related route extensions, primarily because sea ice is typically not particularly extensive in this area. For icebreakers, the average assistance distance increases by about 800 nautical miles over the same ten-year period.

This leads to a combined rise in fuel consumption and CO_2 emissions, as detailed in Table 9.

Table 9: Increase in Fuel Consumption and CO_2 Emissions for Merchant Vessels in the Bothnian Sea, Averaged Over Ten Years.

Distance increase commercial shipping (nm)	**Increased fuel consumption (MT)**	**Increased fuel costs, SEK (mnkr)**	**Increased CO_2-emissions (MT CO_2)**
47 697	2 549	18,2	7 394

For the icebreakers, the total annual increase is shown in Table 10.

Table 10: Increase in Fuel Consumption and CO_2 Emissions for Icebreakers in the Bay of Bothnia, Averaged Over Ten Years.

Increased assistance distance ice breakers (nm)	**Increased fuel consumption (MT) based on 3,5 MT/h at 9 knots**	**Increased fuel costs, SEK (mnkr)**	**Increased CO_2-emissions (MT CO_2)**
812	316	2,2	1 012

4 Societal benefits in relation to increased costs for winter navigation

The following chapter presents the quantifiable aspects of the socio-economic assessment and compares these with the increased costs associated with winter navigation in the Bothnian Sea and the Bay of Bothnia.

4.1 Socio-economic assessment

The socio-economic assessment has been conducted at a high level and incorporates the following considerations:

Renewable Energy Production: This is directly proportional to the installed capacity and the capacity factor (CF). For example, the analysis uses: 1 GW × 0.41 CF × 8,760 hours/year = 3.6 million MWh annually.

Avoided Emissions: These are linked to the extent to which wind power replaces fossil-fuel generated electricity. In the analysis, this equates to 3.6 million MWh/year × approximately 0.075 tCO_2/MWh avoided = roughly 0.27 million tonnes of CO_2 each year.

Employment Opportunities and Local Economic Impact: Both the installed capacity and the stage of development influence these outcomes. During construction, short-term jobs are expected, while the operational phase is assumed to provide stable, long-term positions, which can be related to the number of MW installed. The analysis conservatively estimates 1 job per MW for maintenance and operation. According to CBS (2019), this is around 1.3 jobs per MW per year, equating to about 1,300 full-time equivalents (FTE) annually for 1 GW. Naturvårdsverket (2021) suggests a range of 0.2–10 FTE per MW.

Operation and Maintenance, Cost Calculation Assumptions: A fixed cost per installed MW is used, regardless of output. Ice conditions in the Bay of Bothnia are expected to increase these costs slightly. Benchmark figures for 1 GW: SEK 770,000 per MW annually × 1,000 MW = SEK 77 million per year (Peak Wind, 2022; WindEurope, 2021).

Grid Stability and Export: These benefits have not been quantified. The value depends on how efficiently the electricity produced can be utilised or exported. Increased production reduces the need for imported electricity, supports Nordic grid stability, and may allow for the export of surplus generation.

The monetary value of the above aspects, where available, is summarized in Table 11.

Table 11 Monetary Value of Key Parameters for Societal Benefit

Parameter (monetary value)	Värde	Källa
Renewable Energy Production, SEK/MWh	660 (average)	Elpris SEK 550-770/MWh (Nord Pool historik Sverige & Finland)
Avoided CO_2 emissions SEK/tCO_2	990	EU ETS (market price): SEK 770–990/t (May 2025). Upper value chosen due to assuming higher future prices.
Job opportunities (Operational phase), SEK/year	660 000	(Public statistics) Average salary inkl tax/social fees SEK 550000-715000/FTE/year energy sector
Operation and Maintenance	770000	E.g. WindEurope (2021) – Offshore Wind in Europe – Key trends and statistics (Cites SEK 660,000–SEK880,000/MW/år depending on area)

Regarding the assumptions used for electricity generation calculations, the following values have been sourced from the Swedish Energy Agency: 4,000 full-load hours per year and a power density of 5 MW per square kilometers. For the energy areas included in the calculation, this equates to a total installed capacity of approximately 36 GW in the Bothnian Sea and around 15 GW (for scenario 1) and 23 GW (for scenario 2) in the Bay of Bothnia.

4.1.1 Bay of Bothnia

For the Bay of Bothnia, the total societal benefit in monetary terms is estimated at approximately 63 billion SEK for scenario 1 and 100 billion SEK for scenario 2, as shown in Table 12 and Figure 12.

Table 12 Societal Benefit – Summary of the Monetary Value for Quantifiable Elements, Bay of Bothnia, Scenario 1 and 2.

Bay of Bothnia, mnkr		
Parameter	**Scenario 1**	**Scenario 2**
Renewable Energy Production	38 254,92	60 701,52
Avoided CO_2 emissions	4 303,68	6 828,92
Job opportunities (Operational phase),	9 563,73	15 175,38
Operation and Maintenance	11 157,69	17 704,61
Total	**63 280,01**	**100 410,43**

The estimated value of avoided CO_2 emissions is comparatively low. This is due to the fact that the proportion of electricity generated from fossil fuels is small in both Sweden and Finland.

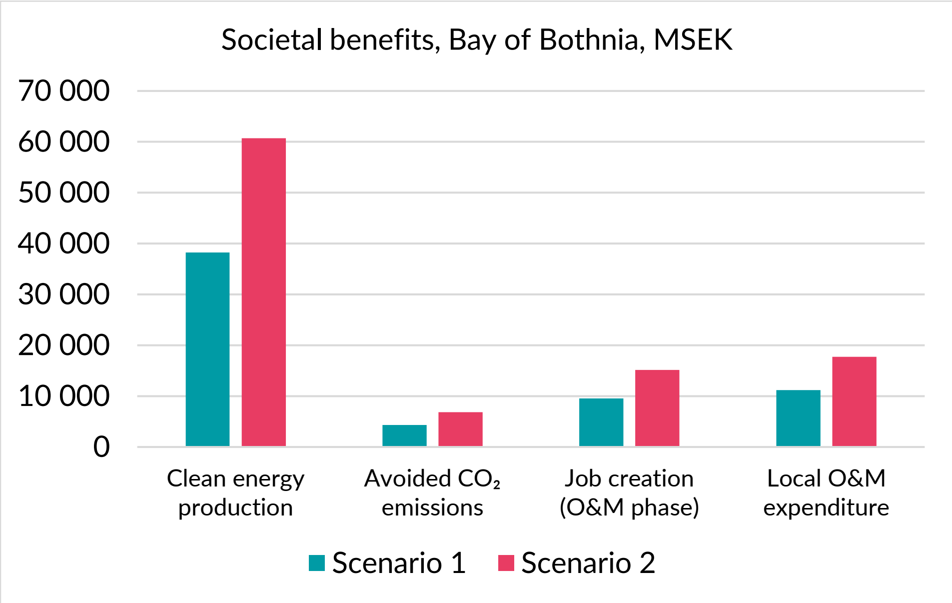

Figure 12: Chart showing the economic benefits to society, expressed in monetary terms, for Bay of Bothnia scenarios 1 and 2.

Below, in Table 13 and in the chart in Figure 13, the increased costs for winter navigation for 2030 are presented.

Table 13 Increased Costs for Winter Navigation, Bay of Bothnia

Bay of Bothnia – Increased cost for winter navigation, MSEK			
Commercial Shipping	Fuel	2,72	5,54
	Operation	1,15	2,33
	CO_2	1,20	2,44
	Total	**5,07**	**10,31**
Ice breaking	Fuel	229,34	275,18
	Operation	340,23	408,24
	CO_2	101,77	122,12
	Total	**671,34**	**805,54**

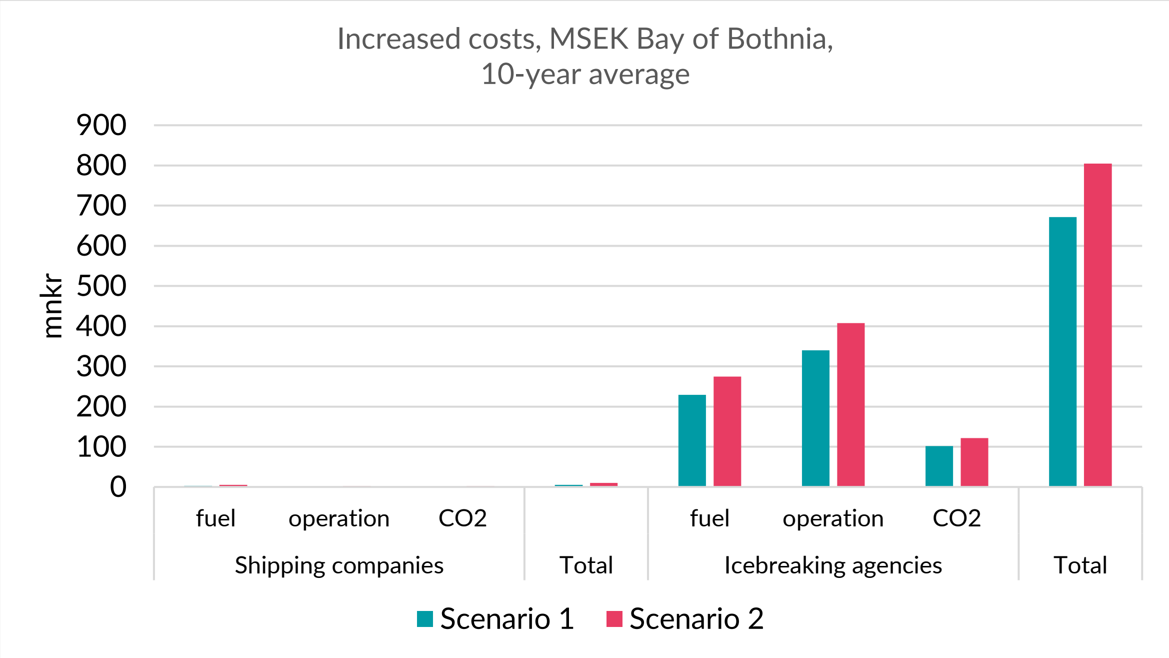

Figure 13 Diagram summarizing the increased costs of winter navigation for scenarios 1 and 2 in the Bay of Bothnia.

In the Bay of Bothnia, it is primarily icebreaker operations that are impacted by the increased costs of winter navigation, as the majority of icebreaking occurs in this area. The additional expenses faced by commercial shipping account for only between 0.75 and 1.26 % of the total cost increase, in scenarios 1 and 2, respectively.

Figure 14 below presents a comparison between the rising costs of winter navigation and the societal benefits of offshore wind power. The comparison shows that the increased costs represent only a small fraction of the societal benefits, roughly 0.8 % for scenario 1 and about 1.1 % for scenario 2.

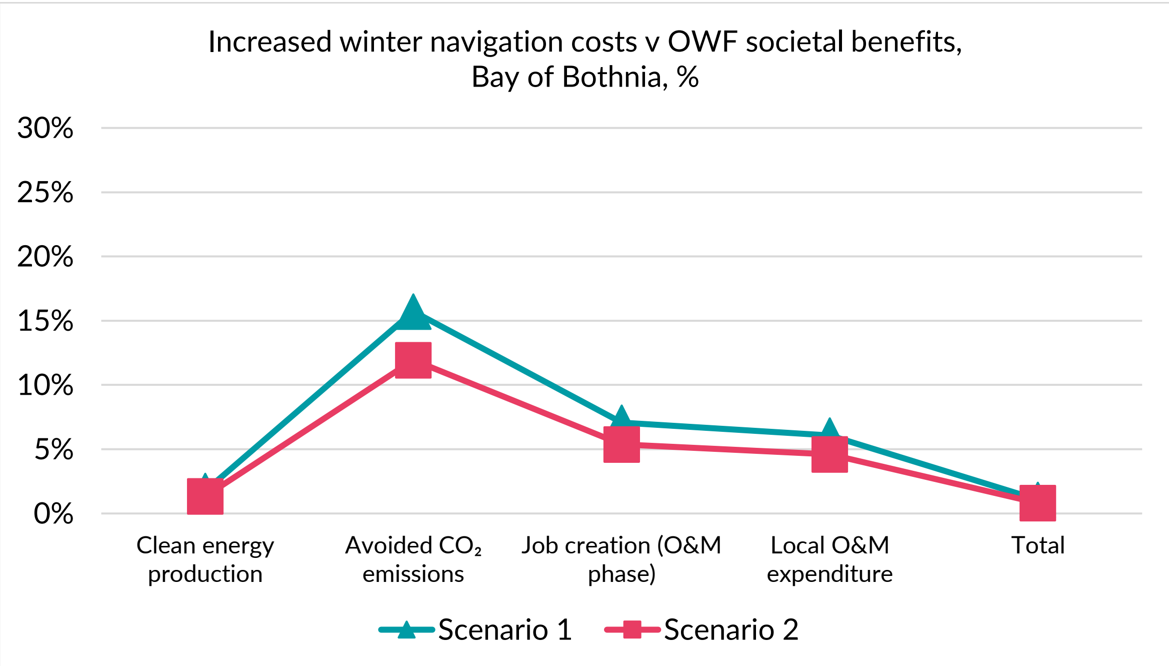

Figure 14 Diagram showing increased costs of winter navigation in comparison with societal benefits

4.1.2 Bothnian Sea

For the Bothnian Sea, the total societal benefit, expressed in monetary terms, amounts to approximately 156 billion, according to Table 14 and Figure 15.

Table 14 Societal Benefit – Summary of the Monetary Value of Quantifiable Components for the Bothnian Sea.

Parameter	Scenario 1
Renewable Energy Production	94 215,00
Avoided CO_2 emissions	10 599,19
Job opportunities (Operational phase),	23 553,75
Operation and Maintenance	27 479,38
Total (MSEK)	**155 847,31**

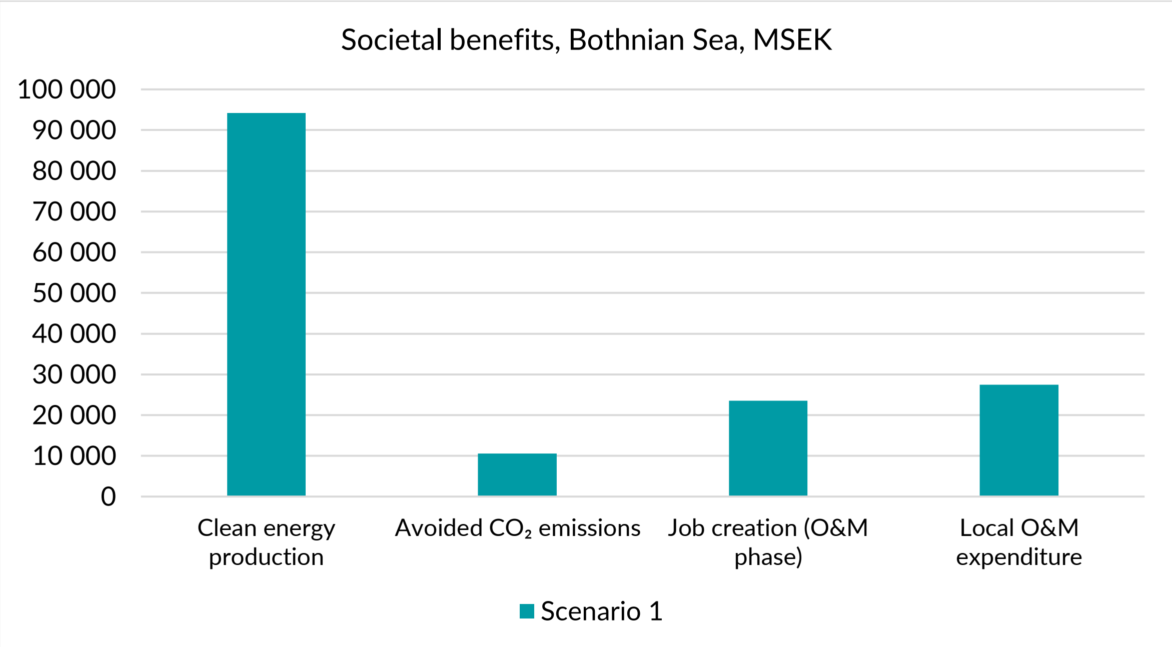

Figure 15. Diagram showing the socio-economic benefits, in monetary value, for the Bothnian Sea.

Below, Table 15 and Figure 16 present a chart illustrating the increased costs associated with winter navigation for the year 2030, based on an average over a ten-year period.

Table 15 Increased Costs of Winter Navigation, Bothnian Sea

Bothnian Sea - Increased cost for winter navigation, MSEK		
Commercial Shipping	Fuel	18,23
	Operation	7,00
	CO_2	8,01
	Total	**33,23**
Ice breaking	Fuel	2,26
	Operation	3,35
	CO_2	1,00
	Total	**6,61**

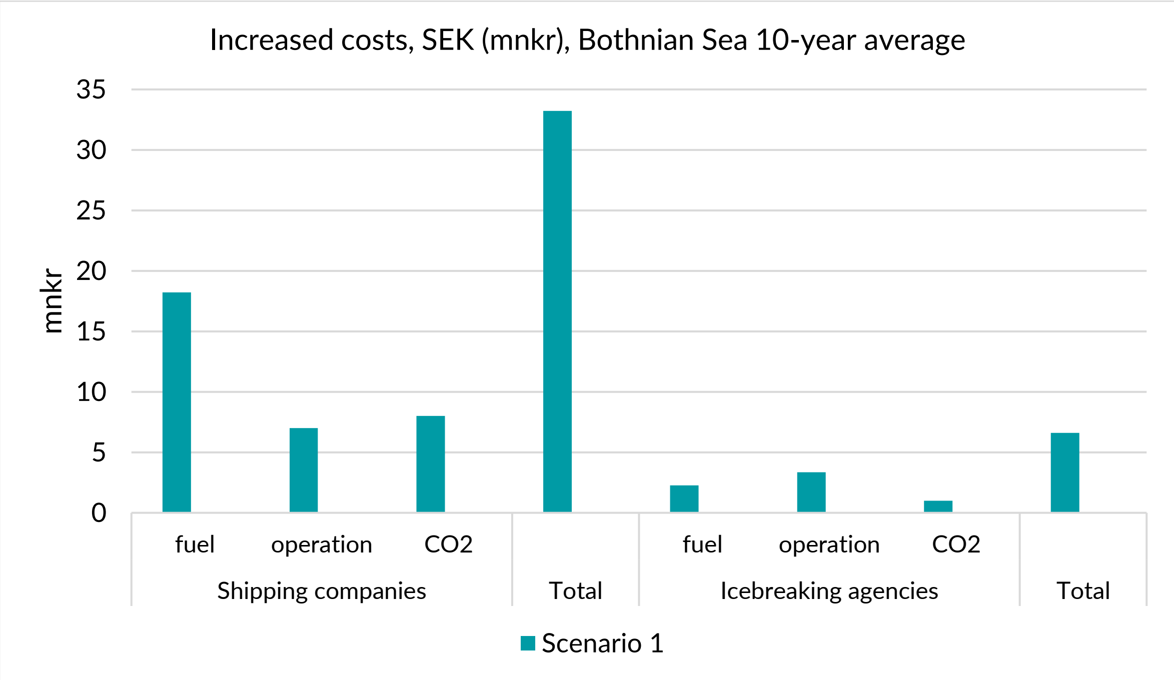

Figure 16 Overview chart of increased costs for winter navigation in the Bothnian Sea.

In the Bothnian Sea, it is primarily commercial shipping that is affected, as ice typically appears for only a brief period each year and is usually limited in both duration and extent. As a result, the demand for icebreaker operations is relatively low. The increased costs faced by commercial shipping account for approximately 83% of the total rise in winter navigation expenses in the Bothnian Sea.

Figure 17 below presents a comparison between the increased costs of winter navigation and the societal benefits (in monetary terms) of offshore wind power. The analysis shows that the overall rise in costs represents merely a small fraction of the total societal benefit, amounting to about 0.03%.

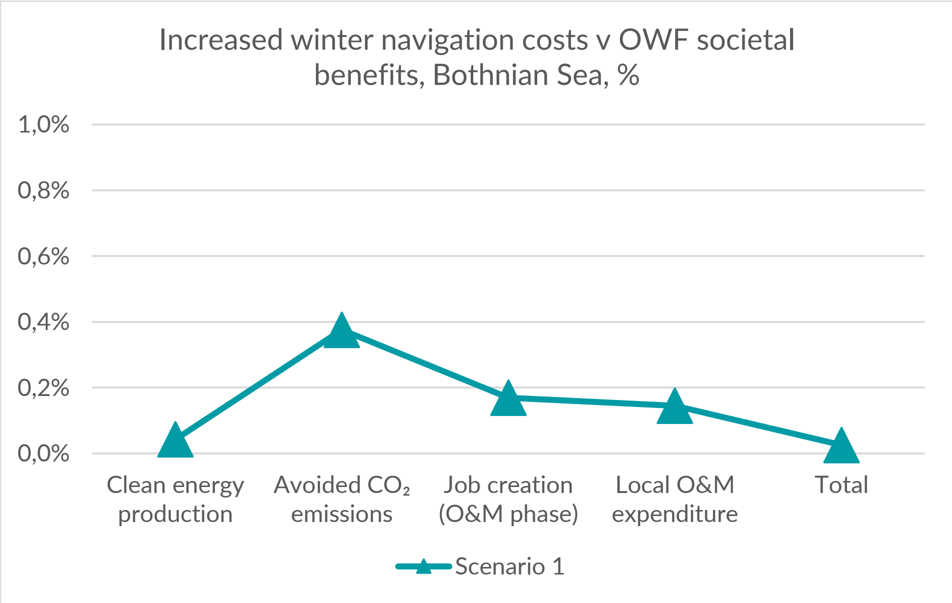

Figure 17 Chart illustrating the increased costs of winter navigation in relation to the societal benefits, for the Bothnian Sea

4.2 Prerequisites for investments in offshore wind

The cost of constructing wind farms is not included in the socioeconomic calculation, as this investment cost is currently expected to be borne by each individual wind farm developer.

At present, due to high investment costs and considerable uncertainty regarding future electricity prices, the market for offshore wind power in Sweden and Finland has slowed down. The current permitting process may also have contributed to this, with lengthy lead times and significant uncertainties. A 2024 review by the Swedish Government Official Reports proposes a shift towards an auction system for offshore wind power in Sweden. Such a system would allow the government to designate suitable and desirable areas for wind farm development at an early stage, considering the collective interests in the sea. The proposal suggests that the developer who wins an auction should be granted exclusive rights to establish wind power in a particular area. Projects could then be developed with substantially lower permitting risks, but with the obligation to actually realize the project. This arrangement could improve conditions for energy and grid planning, as well as for environmental considerations when exploiting the sea for wind power. (SOU2024:89, 2024) However, no decision has yet been made. Finland is also in the process of restructuring its permitting system towards an auction-based procedure. (Finnish Government, 2024)

Regarding the substantial investment costs, there are suggestions for tools to promote new offshore wind power, including proposals in the Electricity Market Review conducted in 2025. (SOU2025:47, 2025) In several other European countries: Denmark, the United Kingdom, Italy and France, dual marginal cost contracts, or so-called Contracts for Difference (CfD), are used to reduce investment risks and thereby financing costs for offshore wind power projects. Poland and Lithuania have also decided to introduce this type of contract in the future. (BWO, 2025) At present, neither Sweden nor Finland employs CfDs, but the Electricity Market Review concludes that state risk-sharing is necessary to make offshore wind power profitable. Consequently, it may be justified to introduce dual-sided Contracts for Difference for offshore wind power to enable investment in new projects. Furthermore, the review suggests that, should such contracts be implemented, an auction-based process for government-designated sites would be preferable in the long run, as it would allow the state to efficiently coordinate grid connections, the location of electricity production, and the management of competing societal interests. (SOU2025:47, 2025)

If the investment cost for building wind power were factored into the overall socioeconomic calculation in this study, the total benefit would be estimated to be roughly four times greater than the investment cost and winter navigation cost combined, for both the Bay of Bothnia and the Bothnian Sea. These calculations are based on the assumption that the investment cost for 1 GW is 25–30 billion SEK and that the operational lifespan of an offshore wind farm is 25–30 years.

5 Analysis

Based on information from the Swedish Maritime Administration, it is assumed that all vessels will require assistance to navigate past wind farms, as they are currently assisted past natural obstacles or through narrow passages. With wind farms established in areas already used by shipping, the available space for vessels is reduced. If ships were to pass a wind farm unassisted and suffer a blackout or being trapped in the ice, there is a risk they could drift into the wind farm possibly alliding[11] with a wind turbine or getting stuck with the wind farm. The need for assistance will, as it does today, depend on ice conditions as well as wind direction and strength. The assumption that every vessel will be assisted on every passage is an overestimate. Nevertheless, for the purposes of this analysis, and to consider a worst-case scenario, it is assumed that all passages past wind farms will require assistance. This means that icebreakers will have to travel longer distances. The increased voyage times may result in longer waiting periods for assistance, which could also be affected by the fact that waiting areas (where vessels can await assistance) may need to be positioned further from the port and away from wind farms. Additionally, the speed at which assistance can be provided may be affected by potentially more challenging ice conditions near wind farms. The analysis assumes a fixed speed of 9 knots for all assistance operations. If ice conditions are more severe, assistance may take place at a slower pace, which could reduce the number of operations possible and further increase waiting times for ships requiring help. The establishment of offshore wind power also means that commercial vessels will often need to take new, generally longer, routes to navigate around one or more wind farm areas.

5.1 Impact on ice breaking operations

The operations will be affected differently in the Bay of Bothnia and the Bothnian Sea, due to the distinct conditions of sea ice in each area. The increased distance as following chapters is calculated based on individual assistance operations, meaning that an icebreaker escorts one vessel at a time. However, there will be occasions when assistance is provided in convoy, allowing several ships to be escorted simultaneously.

5.1.1 Bay of Bothnia

With the introduction of new routes due to the establishment of wind farms according to scenario 1 and 2 as illustrated in Figure 7 of Section 2.3.1, the total increase in assistance distance in the Bay of Bothnia is shown in Table 16 below. The distances are presented as a ten-year average for the winters included in the analysis. In addition, the increased distances for individual years are provided for comparison, as well as the average for the normal winters included in the study. All calculated distances are based on the shipping traffic forecast for 2030, assuming that each vessel receives individual assistance.

[11] Alliding: colliding with a fixed structure - allision vs collision.

Table 16 Increase in assistance distances due to wind farms in the Bay of Bothnia for the winters included in the analysis.

Winter	Inrcreased assistance distance Scenario 1 (M)	Inrcreased assistance distance Scenario 2 (M)
Ten-year average for all types of winters in the analysis	**82 500**	**98 900**
Normal winter average (2017/2018 & 2023/2024)	**118 500**	**140 200**
2010/2011 (severe ice winter, great need for assistance)	119 100	141 000
2017/2018 (normal ice winter, average assistance need)	110 400	130 900
2019/2020 (mild ice winter, small assistance need)	28 200	36 700
2023/2024 (normal ice winter, average assistance need)	126 600	149 600

According to data from the Swedish Maritime Administration (Sjöfartsverket, 2025) and information from the Finnish Transport Infrastructure Agency's website (Trafikledsverket, 2025), the total operational distance covered by icebreakers during 2023/2024 was about 140,000 nautical miles. Although the winter of 2023/2024 was considered normal in terms of ice coverage, it presented significant challenges and demanded considerable resources for icebreaking operations due to turbulent weather conditions and strong, variable winds. These factors caused the ice to compress and create more ridges than usual, at times rendering it impenetrable even for the icebreakers.

When comparing figures, it is important to consider the predicted future assistance distances without the presence of energy areas, i.e., the length of assistance required solely because of increased maritime traffic (scenario 0, for 2030). For 2030, the total assistance distance required by icebreakers under scenario 0 amounts to approximately 320,000 nautical miles for an average winter. The anticipated increase in assistance distance in 2030 with wind farms according to scenario 1 is around 118,500 nautical miles for a typical winter. This means that wind farms, in accordance with energy production areas in scenario 1, are expected to contribute to a 37% increase in assistance distance (44% under scenario 2) during a normal winter.

For the ten-year average of total assistance distance across the winters analysed, scenario 0 is estimated to correspond to about 230,000 nautical miles. The predicted ten-year average increase in scenario 1 is roughly 82,000 nautical miles, indicating that wind farms as per scenario 1 would result in a 36% increase in assistance distance. Scenario 2 would correspond to an increase of approximately 43%. These greater assistance distances will inevitably lead to higher costs and may also result in longer waiting times for icebreaking assistance.

Figure 18 presents a diagram illustrating the estimated assistance distances for 2030 compared to today's calculated distances based on example routes, for both scenario 0 and scenario 1. The diagram shows the average yearly distances for the normal winters included in the analysis as well as a ten-year average covering mild, typical, and severe winters.

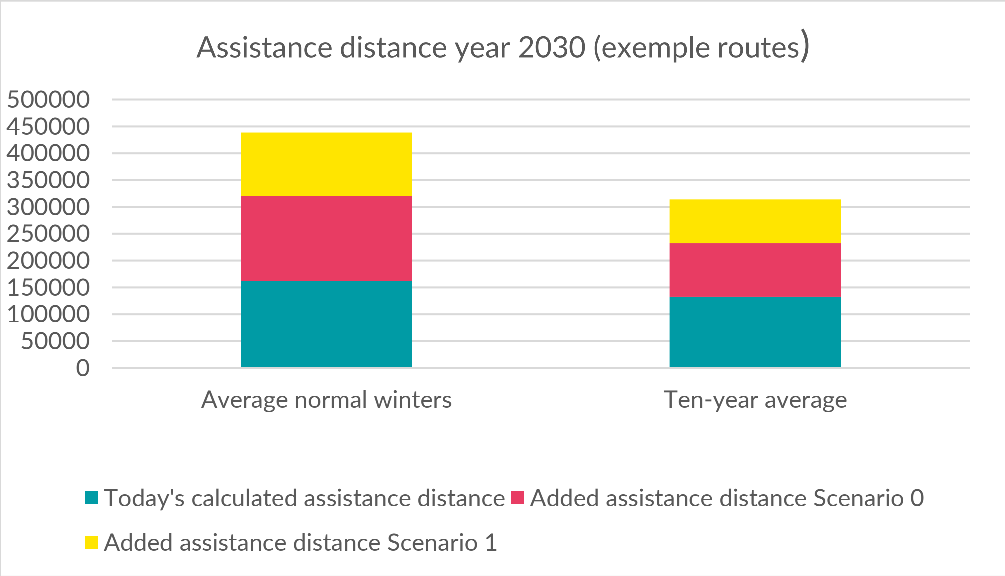

Figure 18 Diagram of total calculated assistance distance in 2030, for the average of normal winters and for the ten-year average across all typical winters

A broader implication also include the need for waiting positions to be situated further from ports, ensuring they are well clear of wind farms. For example, in northern Bay of Bothnia, waiting areas for traffic heading to northern and northeastern ports will need to be relocated further south. One of today's commonly used waiting positions, just south of the EB18 area, may, according to icebreaker captains, need to be positioned centrally in the Bay of Bothnia opposite Bjuröklubb (depending on wind direction) during a typical ice winter. In the southern part of the Bay of Bothnia, there is also a frequently used waiting position 10–15 nautical miles northeast of Nordvalen. Should wind farms be established north of Nordvalen, such a waiting area would instead have to be placed further north, beyond the EB11 energy area and Lunni, as shown in Figure 19.

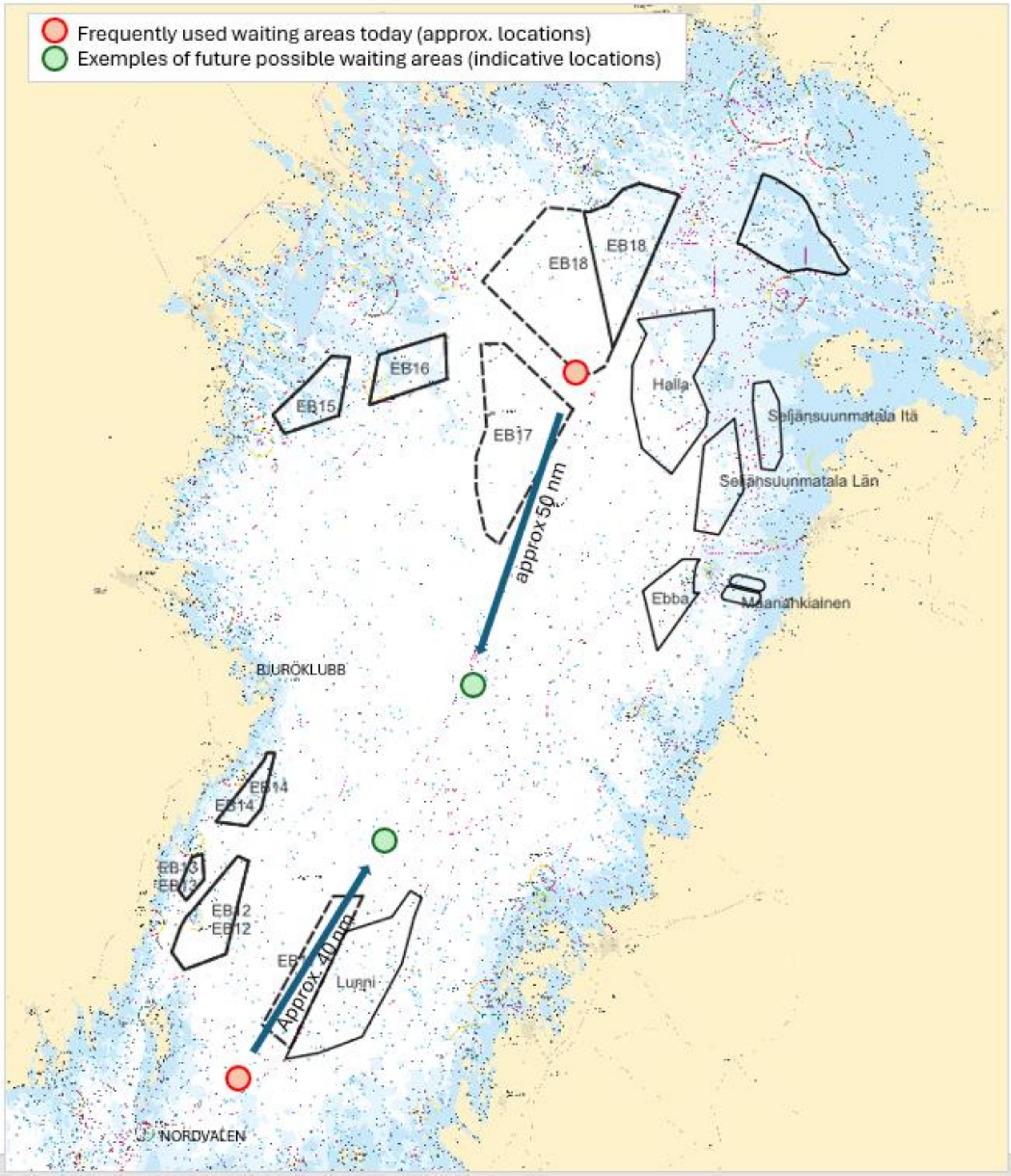

Figure 19 Approximate locations of two currently frequently used waiting positions: one situated south of the EB18 energy area and another north of Nordvalen, along with new potential waiting areas identified by icebreaker captains.

5.1.2 Bothnian Sea

In the Bothnian Sea, icebreakers are not affected to the same degree as in the Bay of Bothnia. This is largely because sea ice requiring icebreaker assistance occurs far less frequently in the Bothnian Sea than it does in the Bay of Bothnia. During a typical winter, such as 2023/2024, and during the maximum ice extent in February, the central part of the southern half of the Bothnian Sea remained ice-free up to the 62nd parallel, roughly between Hudiksvall and Sundsvall, with areas of open ice further east, as illustrated in Figure 20.

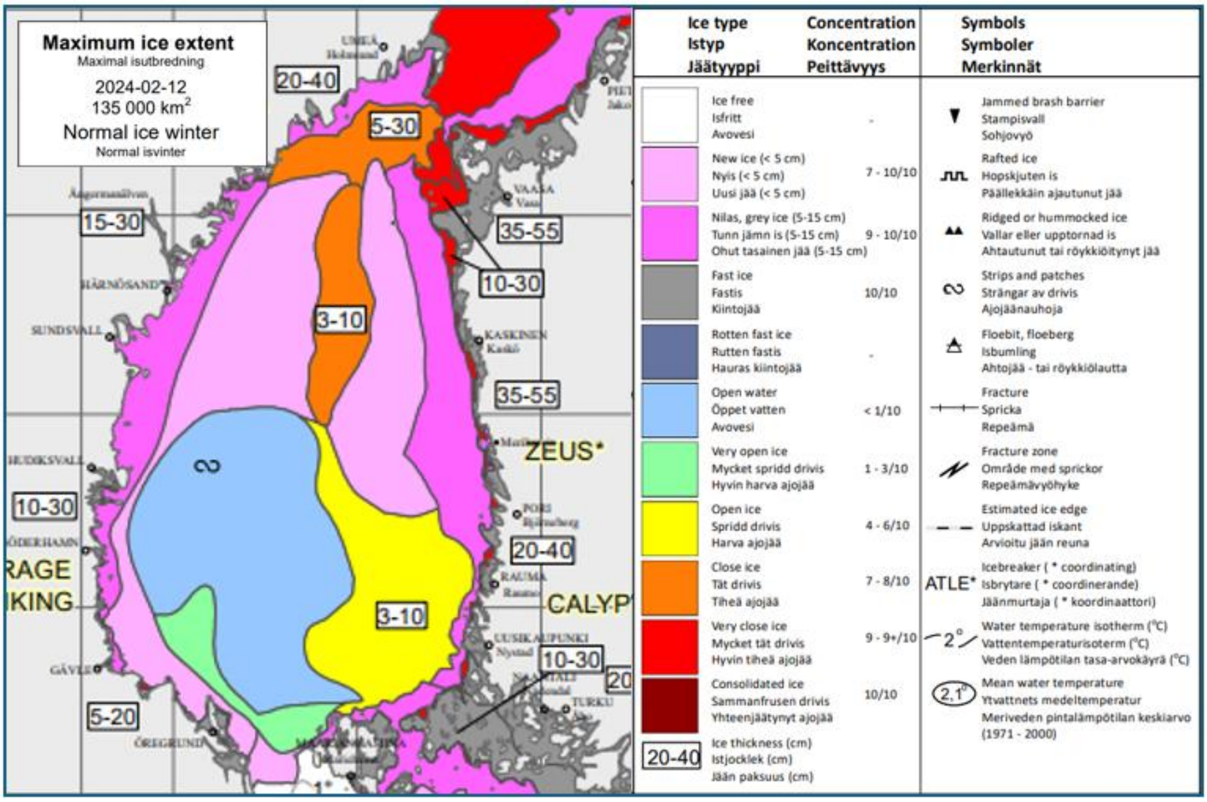

Figure 20 Map of the maximum ice extent during the winter of 2023/2024

With wind farms in the Bothnian Sea, established in accordance with energy production areas as set out in this study, assistance would be required along relatively coastal routes, including to Swedish ports in the southwestern Bothnian Sea and to Finnish ports along the eastern side of the Bothnian Sea. During winters when the need for assistance is high (estimated at one winter in ten), the impact on the icebreakers will be significant, as they would need, for example, to travel north of the wind farms in the southeastern Bothnian Sea to reach ports along the southeastern and eastern Bothnian Sea.

With new routes established as a result of wind farm developments, as depicted in Figure 11 of Chapter 2.3.2, the total increased assistance distance for the ten-year average of the winters analysed is shown in Table 17 below. The increased distances for individual years are also presented for comparison, as well as the distance for the average of normal winters. All calculated distances are based on predicted 2030 traffic levels, assuming that each vessel is assisted individually.

Table 17 Increase in assistance distances due to wind farms in the Bothnian Sea for the winters included in the analysis.

Winter	Increase assistance distance
Ten-year average for all types of winters in the analysis	**810**
Normal winter average (2017/2018 & 2023/2024)	**1580**
2010/2011 (severe ice winter, great need for assistance)	3 380
2017/2018 (normal ice winter, average assistance need)	350
2019/2020 (mild ice winter, small assistance need)	-
2023/2024 (normal ice winter, average assistance need)	2814

The predicted assistance distance for the future, excluding wind farms, i.e., considering only the anticipated increase in traffic and no wind farms (scenario 0, 2030) is estimated to be roughly 10,200 nautical miles for a winter similar to 2023/2024. The calculated increase in assistance required by 2030 due to wind farm development according to the energy production areas as set out in this study is about 1,580 nautical miles, based on the expected average for a normal winter. This means that, in the Bothnian Sea, wind farms are expected to result in an approximate 23 % increase in assistance distance for a typical winter.

For the ten-year average of total assistance distance, covering the winters included in the analysis for scenario 0, the figure corresponds to around 5,500 nautical miles. The estimated increase in assistance for this ten-year average is about 800 nautical miles, indicating that wind farms as per the analysis contribute to an average increase in assistance distance of roughly 15 % over a decade.

Regarding waiting areas in the Bothnian Sea, a commonly designated waiting spot is located 10–15 nautical miles south of Nordvalen. This position is not expected to be affected by the establishment of wind farms in the areas considered in the analysis, as the nearest wind farm is situated more than 20 nautical miles further south (see Figure 21).

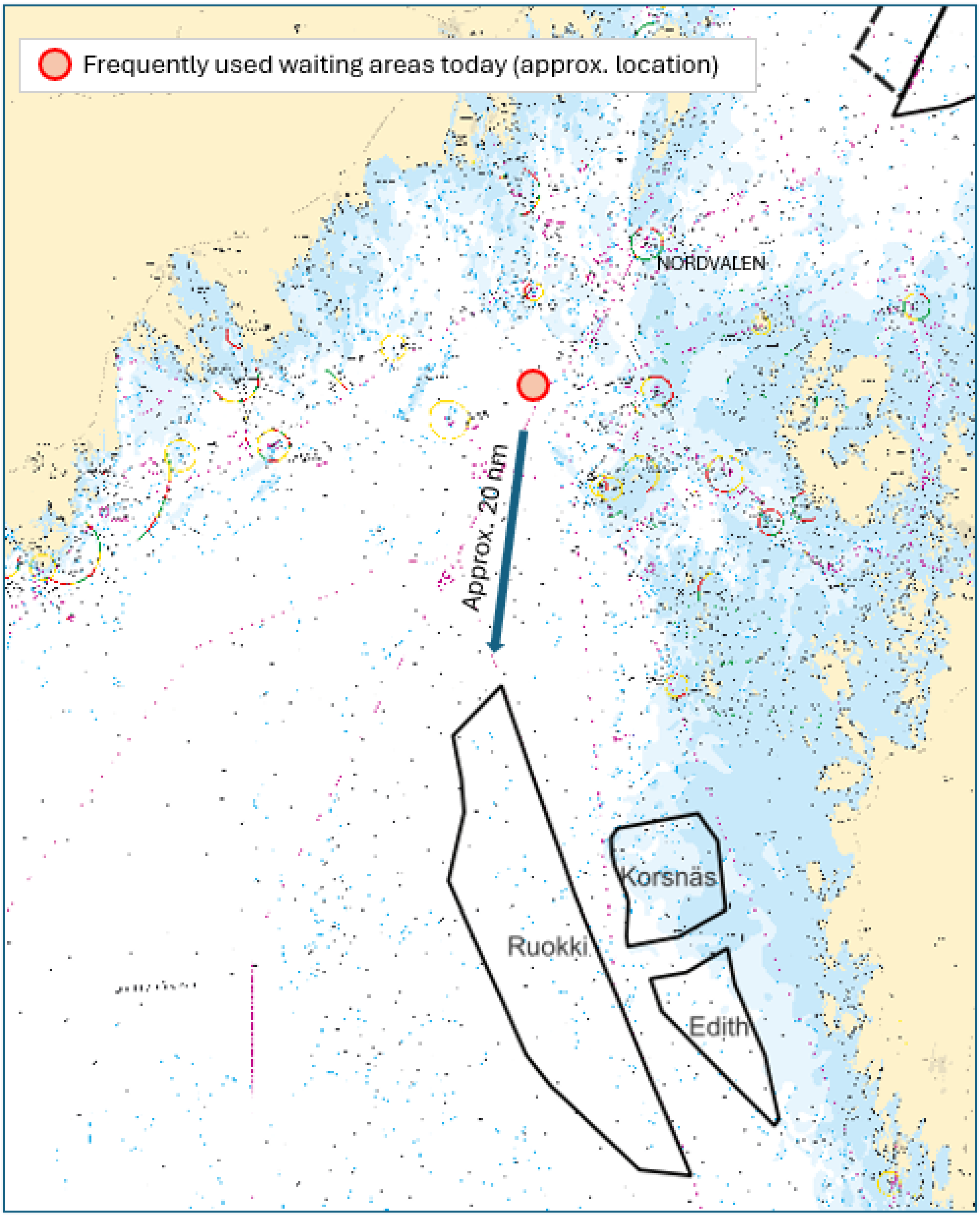

Figure 21 Approximate location of a commonly used waiting area south of Nordvalen.

During the most recent severe ice winter, 2010/2011, vessels were required to wait south of the Svenska Björn lighthouse in the Baltic Sea before being assisted through the Åland Sea and the Bothnian Sea (see figure 22). Should such harsh conditions arise again, it is likely that the outcome would be similar, with that waiting area being unaffected by wind farm developments considered in the analysis.

It is also possible that ships only need assistance through the Åland Sea and Southern Quark, after which they could navigate independently through large parts of the Bothnian Sea if heading towards the Bay of Bothnia or the northern Bothnian Sea. For northbound voyages, the position of the waiting area (south of the Åland Sea) would not be influenced by the establishment of wind farms in the designated energy zones of the analysis. Southbound traffic travelling from the Bothnian Sea to the Åland Sea might need to wait north of Southern Quark. If wind farms are constructed according to the energy areas included in the analysis, the available space for waiting areas in the southern Bothnian Sea would be restricted. Potentially, a location north of Southern Quark could serve as a waiting spot, depending on ice and wind conditions as well as ice drift. See Figure 22.

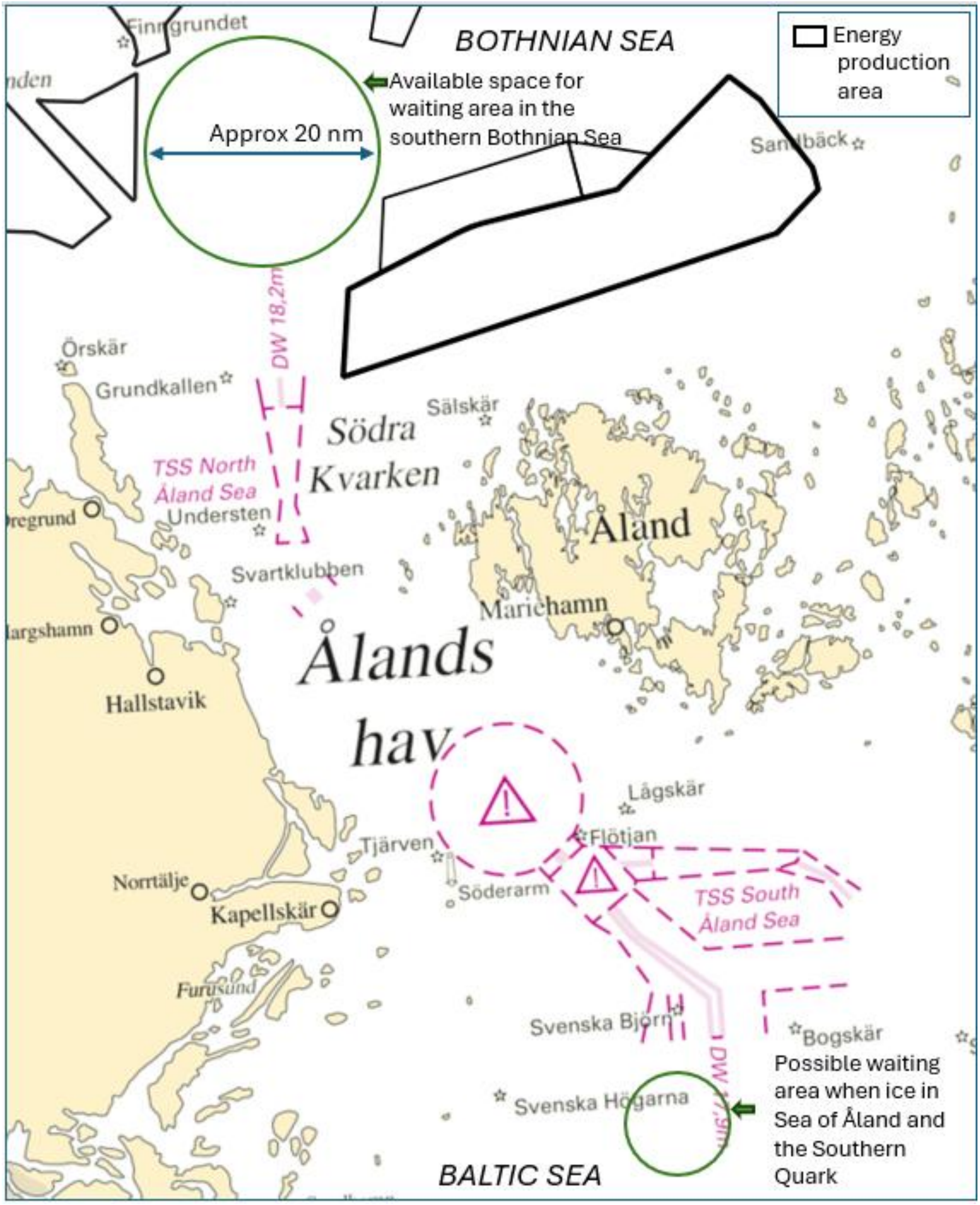

Figure 22 Overview of the southernmost part of the Bothnian Sea, Southern Quark, and the Åland Sea, including available space for designated waiting areas.

5.1.3 Transit

At present, transit operations account for roughly half of all work undertaken by icebreakers. The proportion of icebreaker operations dedicated to transit in the future remains uncertain. The analysis calculations include round trips, with one inbound and one outbound assisted journey. In theory, the next vessel could be brought in immediately after the previous one; however, in reality, ships do not run to a fixed schedule but typically operate within a spot market, decided by cargo flows and berth availability in ports. Icebreaking services are provided to enable ships to access ports during periods of sea ice, with the current objective being to provide assistance within approximately four hours from a vessel's arrival at the designated waiting area. This implies that icebreakers travel in transit to rendezvous with incoming ships, which may be headed for a different port than the previous assisted vessel.

Given the predicted increase in traffic, the current operational patterns will need to be reviewed to maintain the existing level of service, regardless of the development of wind farms. However, it is likely that transit work will be affected by the longer distances required for assistance as a result of wind farm installations.

5.2 Ice breaking resources

The average increase in traffic until 2030 is estimated at around 30% for all ports included in the analysis. For the Bay of Bothnia, this means a total calculated assistance distance of approximately 230,000 nautical miles for the year 2030, including the forecasted traffic increase and based on the ten-year average encompassing mild, normal, and severe ice winters without wind farms. Establishing wind farms in the energy areas as per the analysis is expected to add a further 82,000 nautical miles for scenario 1. For the Bothnian Sea, the equivalent figures are roughly 5,000 nautical miles and just under 1,000 nautical miles, respectively.

Thus, the estimated total assistance distance for 2030, averaged over ten years, is about 235,000 nautical miles for the Gulf of Bothnia, considering only the predicted increase in traffic and across all types of winters. With the establishment of wind farms as per outlined energy areas in the analysis, the total assistance distance in the Gulf of Bothnia is expected to increase by a further 83,000 nautical miles for scenario 1. At present, there are 15 icebreakers available.

During the normal winter of 2023/2024, the assisted distance in the Gulf of Bothnia was around 136,000 nautical miles, according to IBNet data. Publications from the Swedish Maritime Administration summarizing ice winters (Sjöfartsverket, 2024) indicate that the current icebreaking resources were able to manage the traffic flows of such a normal winter, with average waiting times for assistance meeting the target of within four hours. Longer distances have also been managed, however with more icebreakers. Historical data from IBNet shows that the total assisted distance during the severe winter of 2010/2011 was about 236,000 nautical miles, with 16 icebreakers available at the time. This data also includes assistances in the Gulf of Finland.

It should be noted that when the Bothnian Sea becomes ice-covered as it did in the winter of 2010/2011, and the need for assistance in the Bothnian Sea arises, the assistance distances quickly increase due to the long routes involved. This likely contributed to the high total distance covered by icebreakers in 2010/2011.

To handle future increases in traffic, additional icebreaking capacity will be required. On top of this, further capacity is needed due to the expected growth in assistance distance, which is linked to the establishment of wind farms as identified in the analysis. However, how much extra capacity is needed is difficult to determine at this stage, for several reasons: there is an uncertainty regarding the reliability of traffic forecasts, especially the timing of the traffic increase. Moreover, there are significant uncertainties about which energy productions areas will be developed. It is further unclear which wind farms will receive permits, and what the final layout will be for those that are developed. A full-scale development of offshore wind power as per the energy production areas in the analysis is unlikely, as certain adaptations in layout will be necessary to ensure shipping can pass at a safe distance. Additionally, industrial investments in the north are delayed, and there are uncertainties in the market and financial conditions for wind power developers, which must be resolved before investment decisions can be made.

Nevertheless, the predicted future traffic flows suggest an estimated assistance distance of about 235,000 nautical miles in the Bothnian Sea and Bay of Bothnia alone, without any wind farm developments. Compared with historical statistics, 16 icebreakers managed a similar workload in way of travelled distance in 2010/2011, but then handling less traffic. Also, that distance data also includes assistances in Gulf of Finland. Distance data for solely the Bay of Bothnia and the Bothnian Sea is not available, but according to a Baltic Icebreaking Management report, a total of 10 ice breakers operated the Bay of Bothnia and the Bothnian Sea in 2010/2011. (Baltic Icebreaking Management, 2011). The calculated future assistance distance applies for Bay of Bothnia and the Bothnian Sea, but ice breaker assistance is also required in the Gulf of Finland.

It should also be noted that when the Bothnian Sea becomes ice-covered, as during the winter of 2010/2011, and a need for icebreaking assistance arises, the required assistance distances increase rapidly due to the long distances within the Bothnian Sea. This likely contributed to the high total travelled distance by icebreakers during the winter of 2010/2011. It is also worth noting that during 2010/2011, shipping in the Bay of Bothnia was handled by fewer icebreakers than normal, one Swedish and three Finnish from mid-February to the end of March. This was feasible due to the fact that the ice cover in the Bay of Bothnia was very stable during this period, and the broken channels remained open and navigable for longer periods. Since 2010, however, the traffic pattern has changed, and it is unlikely that the Bay of Bothnia can be operated for extended periods with only one Swedish icebreaker.

To manage future increases in maritime traffic, additional icebreaking capacity is needed. Also, further capacity is required due to the expected increase in assistance distances resulting from the establishment of offshore wind power in the energy areas included in the analysis. Determining the exact amount of additional capacity needed is difficult at this stage for several reasons: The reliability of traffic forecasts is uncertain, especially regarding the timing of traffic growth and there are also significant uncertainties concerning which energy production areas that will be developed. Furthermore, it is uncertain which wind farms will obtain permits and how the final spatial layout of the permitted wind farms will look. A full-scale establishment of offshore wind power according to the energy areas used in the analysis is unlikely, as certain adjustments to their layout will be required to allow maritime traffic to pass at safe distances. Additionally, industrial projects in northern Sweden have been delayed, and uncertainties remain in the market and financial conditions for wind-power developers, conditions that must be met before investment decisions can be made.

As mentioned above, future predicted traffic flows result in an estimated assistance distance of approximately 235,000 nautical miles in the Gulf of Bothnia, excluding offshore wind-power development. The establishment of wind farms will also entail additional assistance requirements. How these needs can be addressed depends on which energy productions areas that will be developed. It should also be noted that icebreaking capacity also is required in the Gulf of Finland, as well as in other waters for which the Swedish state is responsible for icebreaking[12], depending on the ice situation.

Furthermore, it is likely that future winters will be more turbulent, causing more difficult ice conditions, which in turn could affect how quickly icebreakers are able to provide assistance. Tougher ice conditions results in slower assistance speed, which also impacts the availability of icebreaking resources.

[12] State icebreaking is carried out in Swedish coastal waters and on the waterways leading to them, as well as in Lake Vänern, between open sea and waters protected from sea ice, drift ice, build ice or similar obstacles. The Swedish Maritime Administration may decide on state icebreaking for more severe ice conditions in the Göta River, Trollhätte Canal, Södertälje Canal, Lake Mälaren and the Ångermanälven. (Swedish Maritime Administration, 2011)

A new Swedish icebreaker is currently on order, and funding for another is included in the proposed National Infrastructure Plan, submitted to the government in September (Trafikverket, 2025). However, these new icebreakers will not increase the total number available, as they are intended to replace two of the existing, older Atle-class icebreakers. In terms of actual resource capacity, the planned new builds will not resolve the need for more icebreakers but are important for renewing the ageing fleet.

One suggestion to possibly help increase icebreaking capacity is to investigate whether the tugboats currently based in ports could be utilised more extensively. There is a difference in how icebreaking is managed in Sweden and Finland. In Sweden, the boundary for state icebreaking is further out in the archipelago, where the build ice begins. In Finland, where more severe ice conditions often prevail due to southwesterly winds, the boundary is much closer in, at the beginning of the port area within the archipelago. If local tugboats could be used more frequently and further out, this could help boost icebreaking capacity. How the costs for such cooperation would be allocated is not covered by the analysis. Figure 23 is an example showing the approach to Luleå, illustrating the current boundary between state and harbour icebreaking at that specific port.

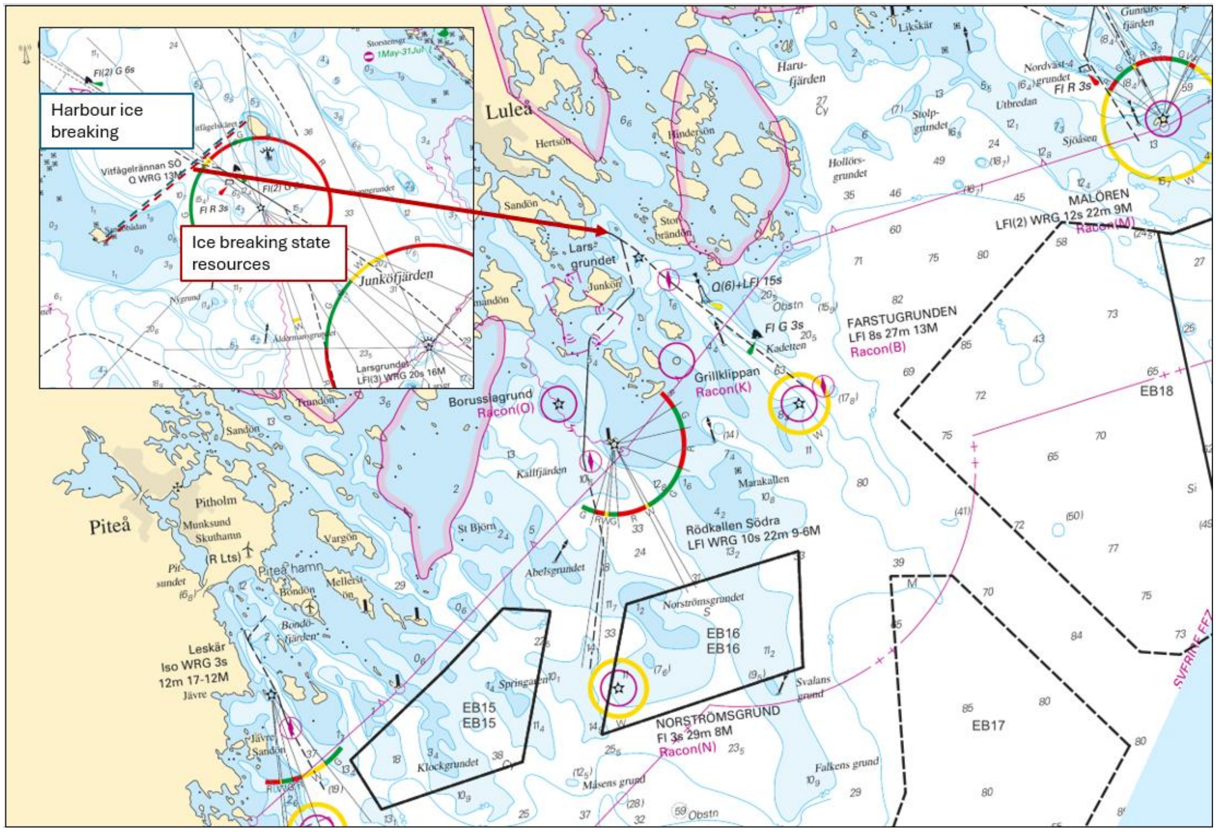

Figure 23 Boundary in Luleå between harbour icebreaking and state icebreaking.

5.3 Impact on commercial shipping

The impact on commercial shipping is limited to calculations of route extensions, increased bunker consumption and emissions. The current assignment does not include a risk assessment of potential increased incident / accident risks due to the combination of sea ice and offshore wind power. Related risk assessments should be conducted once the ongoing ice analysis studies (within the scope of WINMOS III) are completed, in order to properly evaluate how wind farms may affect sea ice and any associated increase in incident / accident risk.

5.3.1 Bay of Bothnia

With the new routes outlined in Figure 7 of Chapter 2.3.1, the total increased distance for all commercial vessels, including the predicted traffic growth up to 2030, amounts to approximately 11,500 nautical miles in Scenario 1 during a normal winter. This corresponds to an increase of just over 1 % compared to the estimated total sailing distance for commercial ships, which is just over 1,000,000 nautical miles.

For both Scenario 1 and Scenario 2, the total route extension from the Northern Quark to the ports in the Bay of Bothnia, according to Table 18, is given for each assumed new route and wind direction. The impact on distance is thus based on the standardised routes used in the analysis, which vary depending on wind direction.

Table 18 Total route extension for each route depending on energy areas according to scenarios 1 and 2, based on wind direction.

Wind direction	Total distance today, from the Northern Quark to port	Impact total distance, scenario 1 (nm)	Impact total distance, scenario 2 (nm)
Northerly (22 %)	974	+5	+979
Easterly (18 %)	1050	-30	+1020
Southerly (27 %)	940	+7	+947
Westerly (33%)	955	+25	+980

Above compilation highlights the minimal impact of energy production areas on route length in the Bay of Bothnia under scenario 1. However, shipping routes may still be affected, as vessels might need to follow partially altered routes, which could involve more challenging conditions than the original routes. However, merchant vessels are only directed along navigable routes, and the primary effect of wind power developments in accordance with energy production areas as set out in the analysis will be on icebreaking operations.

Under scenario 2, the impact on route distance increases, with each wind direction resulting in roughly 1,000 additional nautical miles per year. With an estimated total of around 9,000 vessel passages annually during a typical winter, this means each vessel would, on average, travel 1.1 nautical miles further per route.

It's important to note that only certain routes are negatively affected by increased distances and specific wind conditions, according to estimated example routes. For instance, traffic to Oulu faces a 15 nautical mile longer route in westerly winds, which have occurred 33 % of the time over the past ten winters, in both scenarios. Traffic to Luleå experiences a predicted route extension of 10 nautical miles per voyage in northerly winds (22 % over the last ten winters), again in both scenarios. Kokkola is also affected, with route extensions of 5, 10, or 30 nautical miles depending on wind and scenario. The greatest route extensions due to wind power developments as per energy production areas in the analysis occur on traffic to Oulu and Kokkola. Traffic to Luleå is expected to experience the largest overall route extension, but this is primarily due to the forecasted significant increase in traffic to Luleå, rather than wind power development, as shown in Table 19.

Table 19 Routes in the Bay of Bothnia most affected by the wind power developments included in the analysis.

Route	Number of ship passages with need for assistance 2030.	Increased distance scenario 1 / scenario 2	Increased distance per passage (M)
Northern Quark -Luleå	4001	8680 / 8680	2,2 / 2,2
Northern Quark - Oulu	547	2742 / 3928	5,0 / 7,2
Northern Quark - Kokkola	359	1684 /4503	4,7 / 12,5

In scenario 2, the total increase in distance amounts to approximately 21,800 nautical miles for all commercial vessels during a typical winter with a moderate need for assistance, which represents about 2 % of the estimated total distance travelled. On average, over a ten-year period, the distance increase for commercial shipping is calculated at roughly 7,800 nautical miles for scenario 1 and about 16,000 nautical miles for scenario 2.

5.3.2 Bothnian Sea

In the Bothnian Sea, it is mainly vessels heading to ports in the southwestern part of the area that are affected by the establishment of wind farms as per energy productions areas as set out in the analysis. The implication of such development is longer routes, around the Finngrundet Banks. Overall, these vessels and related ports will experience a significant impact. According to the new routing illustrated in Figure 11 of section 2.3.2, the total additional distance for all commercial vessels, including the predicted increase in traffic up to 2030, is around 81,000 nautical miles during a typical winter with moderate assistance requirements. This corresponds to an increase of approximately 52 % compared to the current estimated total distance of about 155,000 nautical miles. Averaged over a ten-year period, the total distance increase is around 22 nautical miles per voyage during icy conditions, based on an estimated 3,700 vessel passages.

When sea ice, particularly in northerly or northeasterly winds, is present in the southwest of Bothnian Sea, vessels calling the port of Gävle will experience a route extension of roughly 80 nautical miles for each voyage. The port of Gävle is predicted to have the highest number of port calls in 2030. Traffic to Söderhamn and Iggesund is also notably impacted, with each voyage extended by about 20 nautical miles if vessels are required to navigate north of the designated energy areas. On the Finnish side of the Bothnian Sea, routes from the Southern Quark to Kaskinen and Pori are lengthened by approximately 20 and 5 nautical miles respectively.

5.4 Impact on ports

With regard to distance calculations, the analysis assumes that the development of wind farms within the evaluated energy production areas will still allow access to nearby ports, meaning that not all potential approaches will be completely obstructed. Nevertheless, offshore wind power development in certain energy production areas, if outlined as per the analysis, could affect port operations as vessel traffic might be forced to take alternative routes that are potentially longer and more challenging. On the eastern side of the Bay of Bothnia, a channel often opens up during easterly winds, and this passage is frequently used to reduce routes through difficult ice conditions. However, if wind farms are developed to the full extent within these energy areas, there is a risk that shipping routes to Kemi and Oulu via the eastern passage could be blocked, as shown in Figure 24. This situation could, in turn, block winter traffic to these ports, particularly if the route via the Kemi 1 lighthouse is also blocked due to severe ice conditions.

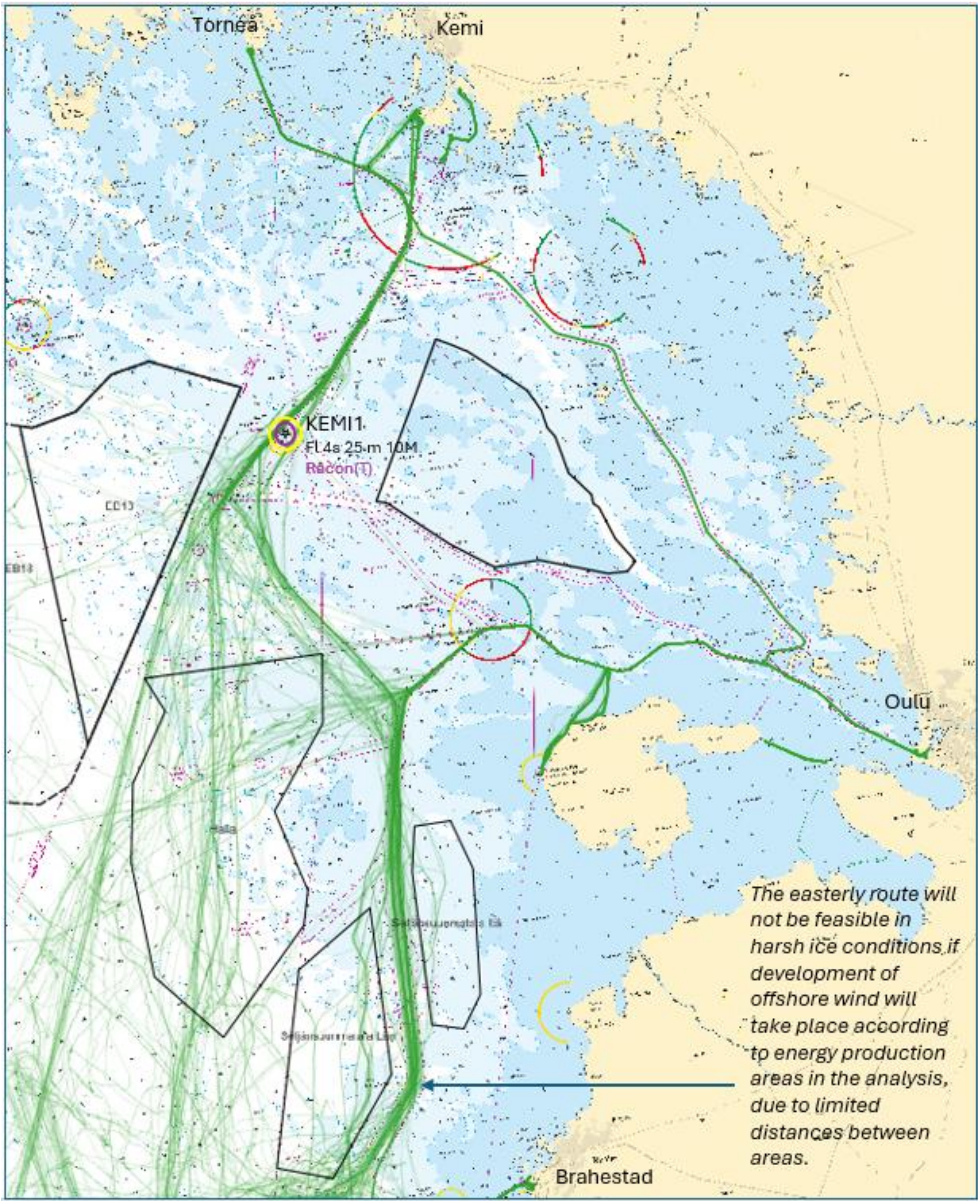

Figure 24 The north-eastern part of the Bay of Bothnia, with designated energy areas and vessel tracks (AIS data) for the winter of 2023/2024 shown in green.

5.5 Increased costs

For icebreaking operations, the increased distances resulting both from higher traffic volumes and the development of offshore wind as per energy production areas in the analysis, does not only entail the need for more icebreakers, but also lead to greater costs, for example in terms of fuel and increased maintenance requirements.

Commercial shipping will also face higher costs arising from route changes due to development of offshore wind, assuming all the energy areas included in the analysis are developed. Longer routes result in increased bunker consumption, and in some cases, extended routes implies that fewer voyages can be completed each year.

While the socio-economic calculation remains broad in scope, it clearly indicates that the additional costs associated with winter navigation are relatively small in comparison to the overall societal benefits connected to wind power development. It should be noted that the current analysis does not account for the capital investment required for any new icebreakers that may be needed.

The question of how to allocate the costs for the increased workload for icebreakers, arising from both port expansions and greater cargo flows as well as from development of offshore wind, is not addressed by this analysis. Nevertheless, this issue will need further consideration by the main stakeholders: the shipping industry, port authorities, wind farm developers, and the government.

6 Discussion on analysis uncertainties

This report is subject to several uncertainties, all of which influence the comparison between the costs of winter navigation and the societal benefits of developing offshore wind power in the Bothnian Sea and Bay of Bothnia.

Routes

Calculations regarding route lengths and icebreaker assistance distances are based on current AIS data and IBNet information, as well as consultations with senior icebreaker officers for potential future routes. It is not feasible to consider every individual route currently used, or potentially used in the future. Instead, the analysis relies on a number of standardised example routes. In the Bay of Bothnia, wind direction and associated typical ice scenarios are taken into account, whereas in the Bothnian Sea, where sea ice is less common, wind conditions are not considered. However, ice scenarios change rapidly, meaning that calculations for extended routes and assistance distances based on example routes and general ice scenarios cannot be expected to fully align with actual operations during a winter season.

Bunker Costs

The lengths of routes and assistance distances, as well as the future need for assistance, directly affect fuel consumption for both commercial vessels and icebreakers. In the analysis, fuel costs for icebreakers are calculated using current prices for MGO/MDO. If there is a transition to fossil-free fuels, fuel costs for icebreakers is expected to double.

Traffic Forecasts

The predicted traffic increase used in the analysis may be somewhat overestimated for the period in question, as the green transition is progressing more slowly than anticipated, and the development of industrial projects in the north is also lagging. For example, the start of the major dredging project in Luleå, part of the Malmporten project scheduled for 2025, has been postponed to 2027. However, the rate of traffic growth and the expected arrival of larger vessels may not necessarily correlate with the dredging project. According to Luleå Port, Stegra, a key player in the port's development, predicts that the number of Panamax vessel calls will rise from today's approximately 18 per year to about 68 calls per year in 2027-2028, as increased volumes of goods to and from the steelworks in Boden are expected. Should dredging not be completed in time for these vessels to enter due to excessive draught, transports will still occur but at designated lightering area outside Luleå. Such a scenario would further increase the number of port calls, as a higher number of smaller vessels would be needed to transport the same volume currently carried by Panamax ships.

Assistance Requirements

The study assumes that the proportion of vessels requiring assistance remains unchanged, but that the distances for assistance become longer due to the need to assist ships past wind farms. All calculated distances are based on 2030 traffic levels, assuming each vessel requiring assistance is supported individually. The analysis does not consider situations where ships are assisted in convoys. For example, if instead two ships were assisted per assistance distance, the estimated increase in icebreaker mileage would be reduced by half. The Finnish Transport Infrastructure Agency notes that there are factors suggesting that the possibility for convoy operations near wind farms will decrease as more wind farms are built, since ice conditions around the farms are expected to worsen. Furthermore, there are indications that today's crews on many of the vessels operating in the Bothnian Sea and Bay of Bothnia have less ice navigation experience than in previous years, which could lead to more individual assistances. However, this is not statistically proven in the current study. Another thing that may affect the need for individual assistance is the EEDI directive[13], which has led to restrictions on engine power in vessels to reduce environmental impact, but also affects ships' ability to operate in ice. The EEDI directive came into force in 2013, and since then newbuilds must adhere to the directive. Therefore, the proportion of vessels with lower engine power will likely increase.

Number of energy production areas developed with offshore wind power

The analysis is based on a set of energy areas, with societal benefits calculated collectively for the Bothnian Sea and Bay of Bothnia. Depending on how many, and which, areas are actually developed, the outcome of the analysis may differ. It is considered unlikely that all the energy areas will be developed, partly because the onshore grid is not sufficiently expanded. This could of course change, but it is not expected to happen in the near future. Offshore wind development to the full extent in all areas identified in the analysis is also regarded as less probable, as certain adjustments will be necessary to allow shipping to pass at a safe distance. Additionally, industrial investments in the north are delayed, and there are uncertainties regarding market and financial conditions for wind farm developers, which must be resolved before investment decisions are made. Wind developers are awaiting government decisions on permit applications and changes in the permit process. Another complicating factor is the absence of guidelines for corridor widths and distances between wind farms, which particularly complicates the permit process in Swedish / Finnish border areas.

If only half of the planned energy production is realized, the societal benefit of offshore wind power is also reduced by half. Nevertheless, the increased costs for winter navigation remain relatively small in comparison.

Investment costs for constructing wind farms in the energy areas covered by the analysis are not included in the socio-economic calculations. If these costs were included into the overall calculations, the total benefit of offshore wind as per energy production areas in the analysis is estimated to be about four times higher than the combined costs for investment and winter navigation, both for the Bay of Bothnia and the Bothnian Sea. If fewer energy production areas are developed, or if the investment cost or the expected lifespan of wind farms is altered from the analysis's estimates, the calculations will be affected.

Route length and assistance distance calculations in this analysis are based on the assumption that vessel traffic can pass either beside or between wind farms in order to reach ports beyond them. This means that not all energy areas can be fully populated with wind turbines. As a result, port operations are not considered to be impacted in this sense. Since the analysis assumes that wind farms will be adapted to allow vessel traffic to reach relevant ports, no calculation is made regarding possible port downtime costs related to wind farms. It is worth noting that there are already occasions when vessels cannot access ports due to severe ice conditions. How offshore wind development should proceed to ensure that ports are not subject to additional downtime due to blocked routes should be analysed, incorporating findings from ongoing studies on the effect of wind farms on ice formation.

If wind farms are established on a smaller scale than assumed in the analysis, the impact will mainly be on icebreaking operations in the Bay of Bothnia, where icebreaking needs are the greatest. The actual impact will depend on which areas that will be developed. If wind farm development should be less extensive in the areas just north of Nordvalen / the Northern Quark, the increased assistance distance to Kokkola will decrease. Furthermore, the frequently used waiting area north of Quark could remain in use. Less extensive wind farm

[13] EEDI Directive: EEDI stands for Energy Efficiency Design Index, an index used to calculate a vessel's energy efficiency, taking into account factors such as emissions, capacity, and speed. The lower the index, the smaller the environmental impact.

development in the northeastern and eastern parts of the Bay of Bothnia, the increase in assistance distances to ports east of these areas will also be reduced.

In the Bothnian Sea, it is primarily commercial shipping that will be affected if fewer energy areas are developed, than those included in the analysis. The greatest impact would result from a reduction in wind farm development in the southwestern Bothnian Sea, as this would reduce route extensions caused by vessel having to navigate north of all energy areas in this region when sea ice is present. Icebreaking activity in the Bothnian Sea is relatively limited, since sea ice occurs less frequently and for shorter periods. However, assistance distances would increase significantly with wind farm developments in the Bothnian Sea for those operations that are necessary, driving up the resource requirements as icebreakers would need to cover longer distances. Should offshore wind not be developed to the extent covered in the analysis, resource needs in the Bothnian Sea may not increase, again depending on which energy production areas that are developed.

7 Conclusions

By 2030, winter navigation will be affected both by increase in vessel traffic and development of offshore wind power, assuming planned wind farm projects will be realized. The predicted traffic growth for all the ports included in the analysis averages about 30 % by 2030. Most ports expect traffic to increase by around 2 % annually from current levels, though a handful anticipate more significant increases. Port of Luleå predicts the most dramatic growth, with traffic predicted to quadruple by 2030.

The anticipated increase in traffic in the Bothnian Sea and Bay of Bothnia is likely to have a substantial impact on winter navigation, particularly icebreaking operations in the Bay of Bothnia, where sea ice always occurs. The need for assistance will increase in line with the growth in traffic. For the Bay of Bothnia, the total assistance distance is estimated to be around 230,000 nautical miles in 2030 as per the calculated ten-year average, considering only the increase in traffic and not considering wind power developments. In the Bothnian Sea, where sea ice is less frequent and less extensive, icebreaking will be affected to a lesser extent, with the increase in assistance distance due to traffic increase alone calculated at approximately 5,500 nautical miles.

The establishment of wind farms in the designated energy areas covered by the analysis will further affect winter navigation, and not just by longer assistance distances or routes. Both commercial shipping and icebreaking operations will be impacted in various ways and to different degrees, depending on the sea area in question. However, the influence of predicted traffic growth is greater than that of wind farm development for the energy areas analysed.

In addition to traffic increase, the establishment of wind farms according to the energy areas in scenario 1 would lead to a further increase in distance for both icebreakers and commercial vessels. For the Bay of Bothnia, icebreaking operations would, again, be affected he most, with an additional increase of about 36 % (around 82,000 nautical miles) in assistance distance, on top of the 230,000 nautical miles estimated for scenario 0, that is, 2030 with only traffic growth considered. With wind farms built as per energy production areas in scenario 2, the increase would be about 43 % (roughly 99,000 nautical miles) from scenario 0.

In the Bothnian Sea, the primary impact would be on commercial shipping, with long diversions leading to a total calculated increase in sailed distance of approximately 50 %. The largest route extensions would affect vessel trading ports in the southwestern Bothnian Sea. Icebreaking operations would only be affected when sea ice is present to a degree that assistance is needed, with an estimated total increase in assistance distance of about 800 nautical miles for the calculated ten-year average. Nonetheless, the assistance distance for those assistances that at times are needed even in the Bothnian Sea would increase considerably if all energy production areas would be developed. This would impact the need for icebreaker resources since the icebreakers would have to cover long distances.

Furthermore, the development of wind farms will impact icebreaking by reducing the number of alternative routes through the ice, potentially making it more challenging to reach ports and increasing the difficulty of the work. This, in turn, could lead to higher fuel and maintenance costs and also be more time-consuming, which may result in a shortage of ice breaking capacity. Ongoing studies on the effect of wind farms on sea ice suggest that wind farms may worsen ice conditions, which could make icebreaking even more difficult.

The analysis assumes that vessel traffic will be able to pass between the specified energy areas when calculating increased distances. When establishing wind farms within these areas, future wind farm layouts will need to adapt to allow for alternative routes through the ice and to ensure that shipping can pass wind farms at an acceptable risk level.

The calculations in this analysis indicate that, in terms of societal benefit, the gains from wind power development by far outweighs the increased costs to winter navigation by, with offshore wind development as per the energy areas analysed. In the Bay of Bothnia, the increased cost for winter navigation represents just over 1 % of the societal benefit of wind power, assuming all energy areas are developed. For the Bothnian Sea, the corresponding figure is 0.03 %. Even when considering the investment cost of building wind farms, currently borne entirely by wind power developers, the societal benefit is still about four times greater than the combined increased cost of winter navigation and wind power investment. A cost distribution is not addressed in this analysis but involves several parties and considerations. Icebreaking operations will face both cost and resource challenges, linked to both predicted traffic increases and wind power development. Commercial shipping, particularly in the Bothnian Sea, will need to manage the cost and time implications of longer routes if wind farms are built according to energy production areas outlined in the analysis. The allocation of costs between stakeholders, shipping companies, ports, wind power developers and the government requires further investigation.

Additionally, a separate study should be conducted regarding the significant societal benefit expected from wind power, relative to its investment cost, in order to establish a risk-sharing and financing mechanism.

For offshore wind power and winter navigation to coexist, governmental overall planning and coordination is necessary, considering the various interests involved. Furthermore, Sweden and Finland should harmonize guidelines regarding the establishment of wind farms near the EEZ border. Common guidelines for corridor widths between adjacent wind farms should also be developed. This is particularly important in the eastern Bay of Bothnia, where several energy areas are set out in close proximity, which, if being developed, would significantly limit alternative routes to nearby ports.

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