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Battery and Charging Infrastructure Sizing Method Applied to the Norwegian Coastal Express

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Executive Summary

In this paper, we present a method for estimating charging infrastructure and onboard battery requirements for ships and show its application to the Norwegian Coastal Route. We approach this challenge with a parametrised model that estimates the percentage of battery-electric operation achievable with different onboard battery capacities, vessel designs, timetables, and charging capacities along the route, in combination with stochastic energy demands due to changing weather conditions and delays. The model can be used as a tool for decision-makers to optimize for battery-electric operation whilst keeping the need for charging infrastructure development at a minimum.

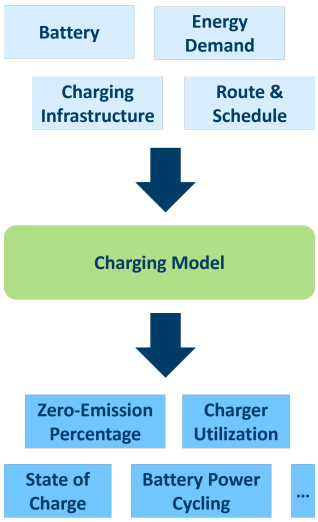
Keywords: Electric Ships, Optimal Charging Locations, Batteries, Modelling & Simulation

1 Introduction

The Norwegian Coastal Express route provides passenger transport and cargo services along the Norwegian coast, connecting 34 ports from Bergen in the south to Kirkenes in the north, as shown in Figure 1b. The full eleven-day round trip covers approximately 2500 nautical miles (4600 km), which is farther than the distance between Portugal and Moscow. Eleven ships are out sailing at any time so that all ports have one northbound and one southbound arrival and departure every day, year-round. The ships in use today are approximately 125 meters long and 19 meters wide, with accommodation for up to 500 people.

Following ambitious goals to reduce global maritime emissions from the International Maritime Organization [1], the European Commission [2], as well as Norwegian national climate goals [3], Hurtigruten Norway AS (one of two operators of the Norwegian Coastal Express) have established the R&D project Sea Zero [4] together with partners from industry and research institutes. Its primary goal is to enable sustainable coastal transport of people and goods by demonstrating zero-emission solutions for the Coastal Express. To this end, a novel vessel design is developed, with significantly reduced propulsion and hotel energy demands, featuring sails, solar cells, and a large battery pack as the primary energy source. The ship is designed for hybrid operation, with a fuel-based (low-carbon) backup energy source, intended for situations outside of expected normal operation, such as extreme weather or unavailable chargers.

The continuous eleven-day round-trip operation along the Norwegian coastline is estimated to require an onboard battery with a size of 60 to 100 MWh and charging power of 6 to 20 MW in several selected ports along the route. This requires an extensive mapping of the conditions in the relevant ports and regional power grids, as well as careful consideration of charging technology, charger power, and the



(a) Illustration of the modelling approach with parameters at the top and outputs at the bottom.

(b) The proposed method can be used to find optimal charger locations and capacities for the Norwegian Coastal Express.

Figure 1: Battery and charging infrastructure dimensioning with the proposed method.

vessel's energy demand and timetable. The competing objectives and limitations represent an extensive optimization problem.

To address this challenge, we present a parametrised model to assess how different onboard batteries, charging infrastructure locations and ratings, vessel design choices, timetables, and varying weather conditions impact the achievable percentage of battery-electric operation for a round trip. We further consider the effects of actual port stay and sailing time variations based on historic AIS (automatic identification system) data from Coastal Express vessels in operation today. Our focus here lies on exploring possibilities to reach different zero-emission targets. While the presented methodology is motivated by the zero-emission efforts for the Norwegian Coastal Express, it can equally be applied to other battery-electric vessels.

2 Method

The parametrised model, hereafter called the *Charging Model*, can be used to explore the achievable percentage of battery-electric operation by simulating the energy flows resulting from charger capacity and location, onboard battery capacity, round-trip timetables, and energy requirements for different weather conditions and sailing speeds. Figure 1a illustrates the model's functionality. The following sections are devoted to describing the model parameters and outputs, as well as the underlying assumptions and simulation logic.

2.1 Parameters

The parameters (at the top of Figure 1a) are modelling the factors whose effects are studied in this work: the battery, the charging infrastructure, and the vessel's timetable. This section details the syntax and semantics of the Charging Model's parameters.

Energy demand. The net amount of energy that needs to be supplied to propulsion and hotel system[1], depends on multiple factors such as weather conditions, ship design, and propulsion technology. Therefore, it is to be calculated in a separate step and given to the Charging Model as an input. For example,

[1]The net energy includes any additional energy that needs to be supplied to account for losses within the propulsion and hotel system, i.e. the energy that needs to be supplied from the battery or the chargers to the ship's energy system. Losses within the battery system are specific to the battery system as opposed to ship design and propulsion, and therefore not included in the energy demand parameter. Instead, they are a modelled in the battery parameter.

the input dataset may represent a worst case of an inefficient ship design in harsh winter weather, or a more efficient ship sailing in less demanding conditions. Hence, the Charging Model specifies the *format* of the input data, whereas the *method* of calculating the energy demand input data is not relevant to the Charging Model's operation. Accordingly, only the energy demand parameter format is described in this section. The method of calculating this input data may vary for different case studies, and the method used in this work's case study is described together with the case study in Section 3.

This parameter set is split into the energy demand during port stays and the energy demand while at sea. These are given as a function of time, used to calculate the energy demand based on the duration of the port stay or stretch between two ports, in the following referred to as *sailing leg*. For port stays, the average power demand during the stay is given as one value and multiplied with the duration to obtain the energy demand. For sailing legs, however, the power demand depends on the sailing speed. Therefore, the average power demand as a function of sailing time is provided to the Charging Model in the form of one polynomial per sailing leg. Optionally, the valid range of sailing times for which each polynomial yields a meaningful average power demand can also be specified. The port stay is defined as the time during which the ship is secured at the quay. The energy demand for any manoeuvring in the port and mooring of the ship is assumed to be included in the energy demand for the sailing leg.

Battery. The battery is described by its net size s, a charging loss approximation function l_{c}, and a discharging loss approximation function l_{d}.

The battery net size s is defined as the difference between a given minimum state of charge (*SoC*) and a given maximum SoC. Accordingly, in the remainder of the paper, we say the battery is empty, when the SoC is at the defined minimum and should not be discharged further, and full, when it is at the defined maximum and should not be charged further. The gross size is the battery capacity required to guarantee the defined net size throughout the battery's lifetime. Its calculation depends on outputs of the network model, for example the battery load flow data during operation, as well as the planned lifetime of the battery. Therefore, detailed modelling of the battery as well as the calculation of the gross size are outside the scope of the Charging Model.

The charging and discharging loss approximation functions, l_{c} and l_{d}, respectively, can be chosen freely to approximate all losses within the battery and onboard charging equipment, including power converter losses. Discharging losses do not include any losses in the ship's internal power distribution system. Instead, these are assumed to be included in the energy demand input. The loss approximation functions allow to estimate losses from charging or discharging duration and power, as well as the current SoC.

Charging infrastructure. The charging infrastructure is represented as a system of available chargers at selected ports along the route. Each charger is defined by its location (the port) and the maximum power it can deliver to the ship, after any on-shore losses are taken into account through the value representing the maximum power: it represents the maximum power that can be delivered to the ship, not the power supplied to the charger. In practice, the chargers must therefore be designed with a higher rated input capacity to compensate for these losses. If relevant, connection and disconnection time as well as any additional energy needed onboard the ship for connecting or disconnecting the charger can be specified.

Timetable. A timetable is defined by a sequence of port stays including arrival and departure times. When speaking about the Charging Model parameter, we refer to a *schedule*, where one schedule can include one or more timetables. This allows us to represent variations over the simulated time period, for example due to different timetables for summer and winter operation.

The scheduled arrival and departure times are defined as the start and end of the time frame within which the ship is secured , such that cargo can be handled and passengers can board and leave the ship, i.e. the times that would be found in a published timetable. The time needed for manoeuvring in the port and mooringare therefore assumed to be included in the sailing time rather than the port stay.

2.2 Simulation Method

In the Charging Model, one round trip is simulated according to the given timetable. Port stays and sailing legs are simulated in order of sequence as shown in Algorithm 1. In each step, simulation data is collected, including

- start time,
- port (destination port for sailing legs),
- battery state of charge (SoC),
- time when reaching the battery limit (if the battery is emptied or charged fully during the interval),
- average battery load flow,
- energy delivered to ship,
- energy delivered from battery,
- energy delivered as shore power,
- energy delivered from alternative source, and
- energy delivered from chargers.

This output data can then be used for further analysis, including calculating the percentage of battery-electric operation and other relevant metrics. Based on sailing and port stay durations from the given timetable, energy demand is calculated for each sailing leg (E_s) and port stay (E_p). Furthermore, the total energy available from the respective charger (E_c) is calculated for each port stay[2].

Algorithm 1: Round Trip Simulation

```
for (sailing leg s and following port stay p) do
    // simulate sailing leg
    battery.discharge(E_s)
    // calculate and save simulation data

    // simulate port stay
    if E_p > E_c then
        battery.discharge(E_p − E_c)
        // calculate and save simulation data
    else  // E_p ≤ E_c
        battery.charge(E_c − E_p)
        // calculate and save simulation data
```

For each sailing leg, energy is supplied from the battery or, if the battery is empty, from the backup energy source. For the port stays, the difference between E_p and E_c determines if the battery can be charged or if energy needs to be supplied from the battery or an alternative energy source. The functions `battery.charge` and `battery.discharge` track battery parameters during simulation. Charging and discharging is restricted to the battery net size, and the point in time when the battery is maximally charged or discharged is stored as simulation data, along with how much energy was transferred before the limit was reached.

Depending on the chosen technology, the charger connection time can be handled in three different ways during simulation:

1. If the charger is connected *after* mooring, the connection time is subtracted from the duration of each port stay.
2. If the charger connection can be established *while* mooring without requiring any extra time, the connection time is not taken into account when calculating sailing and port stay duration.
3. If the charger has to be connected *before* the ship can be regarded as secured to the quay, but connection adds time to the process of mooring and securing, the connection time is subtracted from the duration of the sailing interval.

The time needed to disconnect the charger for departure is treated analogously.

2.3 Analysis of Available Charging Times

To represent available charging times more realistically, historic punctuality of port stays can be analysed using AIS (automatic identification system) data. Here, and for the case study described in Section 3, we obtained AIS data for all Hurtigruten vessels that were sailing on the *Bergen–Kirkenes* route in the time between 2022-01-01 and 2023-06-30. This period was chosen as the most recent available one for which the after-effects of the COVID-19 pandemic are assumed to have subsided sufficiently. The data source is the Norwegian Coastal Administration, and the data is subject to the NLOD license[3]. There are no geographic limitations to the data, but transmissions (via satellite) are sporadic outside of Norwegian waters.

Comprehensive data processing and analysis his generally required to gather representative statistics on the times spent at each port based on the following steps:

- Check the data for missing or unreliable values.
- Clean the data and fill any gaps in a manner which reduces the chance to introduce biases.
- Identify stationary time periods, for example, based on speed over ground (SoG) and AIS message frequency.
- Identify individual sailing legs and port stays by matching vessel locations to known port locations.
- Filter for spurious results stemming from manoeuvring close to quay or AIS drop-outs.

[2] $E_c = 0$ if no charger is installed in the respective port.

[3] See `https://data.norge.no/nlod/en/2.0`

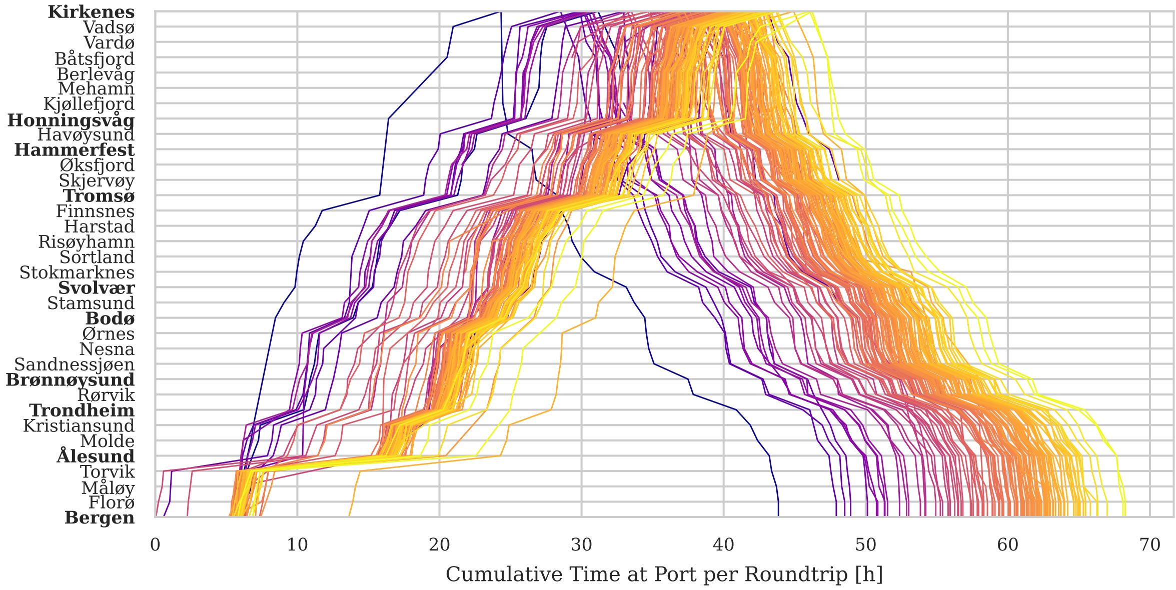


Figure 2: Variability of the time spent at port for 124 complete round trips selected from the winter and spring seasons in the periods of 01.01.–31.05.2022 and 01.11.2022–31.05.2023. These cumulative times illustrate a theoretical upper bound for the time available for charging.

From such processing, full round trips (Bergen–Kirkenes–Bergen) were collected for which the expected sequence of port stays could be identified from the AIS data with reasonable confidence. A significant number of round trips had to be discarded due to missing values or insufficient confidence in the results. Despite great care, the described processing and selection will certainly introduce a bias in the final statistical results. However, we are here interested in illustrating general methodology, and a more rigorous analysis of biases is outside the scope of the present work.

As illustrated by Figure 2, significant deviations can be observed in the times spent at port due to delays. Such delays often stem from unfavourable weather which, in some cases, can force ships to wait for conditions to improve. These statistics can be fed into the Charging Model to gauge the sensitivity of results as a function of time delays and deviations, and are thus an integral part in finding optimal and robust infrastructure and vessel design choices.

3 Case Study

In this section, we apply the presented methodology to the Norwegian Coastal Express case, described in Section 1, and demonstrate how the Charging Model can be used to model and analyse the case. First, Section 3.1 details how the input data for the energy demand parameter is calculated to represent the Coastal Express scenario, and Section 3.2 presents the model parameter setting representing other given conditions. Then, Section 3.3 exemplifies how the Charging Model can be used to analyse the scenario and provide decision support.

Because the work within the Sea Zero project to reduce the energy demand of a new generation of ships is ongoing, we will use the simulated energy demand for one of the existing vessels that are currently serving the route to demonstrate the use of the Charging Model. Consequently, this article does not provide conclusions for energy demand, battery capacity, and charger power, and the figures shown focus on comparing different battery and infrastructure scenarios without quantifying the absolute energy or power values. The approach will later be applied with the final ship design, and final demand data along with battery and infrastructure recommendations or decisions may be published once the project activities are concluded.

3.1 Calculation of Energy Demand Input

To achieve realistic results from the Charging Model, the input energy demand described in Section 2.1 is estimated using the Gymir simulation platform [5, 6]. Gymir applies ship models and hindcast weather data to simulate the transit phase of ship operations for an extended period of time, in this case the route along the Norwegian Coast for the year 2022. Due to the Charging Model's input requirement, Gymir simulates each (port-to-port) sailing leg independently. With basis in the route timetable, each leg is simulated one time each day for the whole year, each voyage starting at the time of day specified in the route timetable. Geiranger and Urke are only visited during limited periods of the summer season.

All legs are sailed at 11.5, 12.5, 13.5, 14.5, and 15.5 knots, and for each speed, a distribution function for the average power demand is estimated. This distribution is then used to estimate 50^{th} and 90^{th} percentiles which, in turn, are used to fit the coefficients of the polynomials provided to the Charging Model to infer average power demands for a given sailing duration.

Hindcast Weather data. The Coastal Express is dominated by sailing close to mountains and in fjords, and impacted by local weather and sea conditions. Using weather data that takes this into account is important to estimate energy demands. For this study, a model with grid size of 800 meters from MET Norway is used.

Ship model. Energy demands are calculated using the ship MS Trollfjord as a benchmark case. It is modelled in the ship design suite ShipX [7] to generate a quasi-static model for Gymir [8]. Given speed-over-ground, wind, sea state, and sea current, we estimate the steady-state power demand for propulsion based on

1. calm water resistance from Computational Fluid Dynamics (CFD) calculations,
2. wave resistance by VERES, a potential flow code in ShipX [9],
3. propulsion efficiency coefficients from Computational Fluid Dynamics (CFD) calculations, and
4. wind resistance from empirical models [10].

In addition, resistance models 1-3 are calibrated from scale model tests in SINTEF Ocean's lab facilities. To account for non-propulsion consumers such as hotel, ventilation, and air condition (HVAC), a static power demand is added during transit simulation.

3.2 Parameter Setting and Ranges

For some of the parameters, possible values are restricted by physical limitations (battery losses and available charging power from the grid) or set goals and criteria (route and timetable). This section explains the translation of such limitations into parameter values and ranges.

As a starting point for the schedule parameter in this case study, we are using the Coastal Express timetable for 2022. This timetable differs for the different seasons: The winter-spring timetable, valid from November to May, presents the base case and includes a ten-hour-stay in Ålesund on the northbound journey. During the other seasons, this stay is interrupted by an eight-hour-excursion to Hjørundfjorden in September and October (autumn timetable), and a nine-hour-excursion to Geirangerfjorden from June to August (summer timetable). Consequently, the schedule parameter consists of three separate timetables for winter-spring, summer, and autumn.

For this study, we consider charging only at the ten ports with the longest stays, with 105 minutes or more on southbound or northbound journey. Ports with shorter stays are not considered relevant,due to high investment costs for the respective infrastructure and suboptimal usage of the installed capacity. For this study, the charger connection time is assumed to be relatively short (up to 5 minutes) and included in the process of mooring and securing the ship.

Charging and discharging losses are approximated with a fixed 2.5% of the battery power flow each. This is deemed sufficiently accurate since no specific type of battery has been selected yet. The energy exchange between battery and vessel is then given by:

$$\begin{aligned} \mathrm{E}_{\text{to ship}} &= \mathrm{E}_{\text{from storage}} - l_{\mathrm{d}}(\mathrm{E}_{\text{from storage}}) = \mathrm{E}_{\text{from storage}} - 0.025 \cdot \mathrm{E}_{\text{from storage}}, && \text{for discharging,} \\ \mathrm{E}_{\text{to storage}} &= \mathrm{E}_{\text{from charger}} - l_{\mathrm{c}}(\mathrm{E}_{\text{from charger}}) = \mathrm{E}_{\text{from charger}} - 0.025 \cdot \mathrm{E}_{\text{from charger}}, && \text{for charging.} \end{aligned} \tag{1}$$

Upgrading the power grid is time-consuming, which may result in temporary limitations on the power available from the grid. Additionally, constraints on investment budgets can restrict both grid connection capacity and charging infrastructure. Here, however, we focus on exploring the implications of different charger sizes on battery-electric operation and therefore do not impose any limitations.

3.3 Results

Using the parameters described above, the Charging Model can be used to analyse the impact of different choices for battery capacity, charging infrastructure, and timetable, as well as different goals for electric operation.

For transportation governed by a public tender, as it is the case for the Norwegian Coastal Express, tender criteria may require a minimum percentage of battery-electric operation. As an example, a set target may be to operate each sailing with 100% battery-electric energy at least 90% of the time. In the Charging Model, this goal translates to setting the energy demand parameter to the 90^{th} percentile

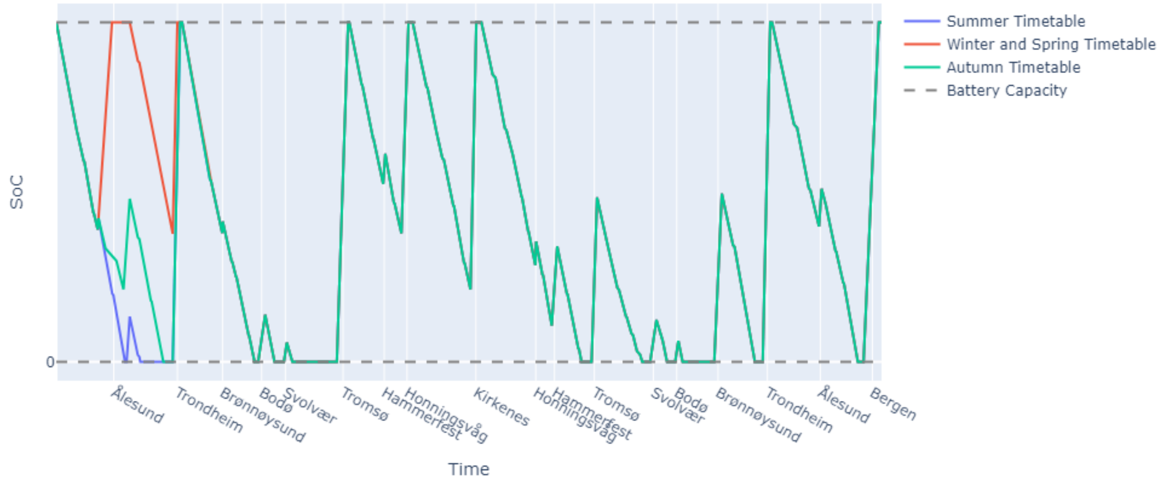


Figure 3: The state of charge (SoC) during the round trip journey (Bergen–Kirkenes–Bergen) of a Norwegian Coastal Express ship for one charging infrastructure scenario.

(the energy covering 90% of the trips). Additionally, the tender criteria may restrict route and timetable, either by setting a fixed timetable, potentially varying throughout the seasons, or criteria for adaptions in route and timetables. The following paragraphs exemplify how the Charging Model can be used to support decisions on charging infrastructure and battery capacity in order to fulfil different goals.

In this example, we assume that the tender calls for operation according to the current timetable, featuring excursions from Ålesund on the northbound journey during summer and autumn. This can be represented using three timetables for the timetable parameter as described in Section 3.2. As a starting point, we set the battery net size as well as the power of the chargers in the different ports to an initial guess. Simulating this scenario results in a battery-electric percentage of 82.92% for the winter timetable, and 81.57% aggregated for one year. This can now be analysed for hints on battery net size and charging infrastructure choices for reaching 100% electric operation.

A central visualisation of the simulated scenario shows change in the battery SoC throughout the journey, as shown in Figure 3. If several timetable options describe a round trip journey of the same length, the SoC can be visualised alongside each other. Note, however, that the x-axis labels only align meaningfully across all timetables if ports are visited in the same order and time frame. In these visualisations of the SoC throughout the journey, periods during which the SoC is zero indicate that the energy demand of the ship has to be supplied from a different source. During periods where the SoC is at battery capacity, the energy demand of the ship is supplied directly from the charger and the battery is full and therefore not charging.

We may note that the a given timetable and energy demand define a lower bound for the battery capacity: the energy demand needed for the longest period without charging needs to be supplied by a single battery charge. In the scenario at hand, this is strictly spoken the sailing leg between Honningsvåg and Kirkenes. However, the timetable for the northbound journey allows only for a ten-minute port stay in Brønnøysund, and as a consequence, the amount of energy that can be charged will not be significant for any realistic charger power value. We can therefore assume the energy demand for the sailing from Trondheim to Bodø defines a minimum value for the battery net size.

To achieve 100% battery-electric operation, we need to adapt battery capacity and charging infrastructure to avoid a depleted battery during the full round trip. For example, Figure 3 shows one period with a depleted battery before arrival in Bergen, and the SoC behaviour prior to the depletion can guide adaption of the charging infrastructure: Increasing the charging power in previous ports only has an effect if the battery is not fully charged after. In this example, increasing the charger capacity in Brønnøysund will not change the outcome, because no additional energy can be stored when reaching Trondheim (visible in Figure 3 as a full battery), while increasing charging power in Ålesund will be effective due to free battery capacity. Alternatively, new chargers may be introduced in other ports. Similarly, increasing the battery capacity only has an effect if there are charging ports where there is more energy available than what can be stored, visualised by periods where the SoC is equal to the battery capacity in Figure 3.

When adapting the charging infrastructure, it may be relevant to consider to what extend the installed charger can be exploited. This is impacted by two factors: the duration of the port stay, considering both the northbound and southbound journey, and the free capacity in the battery when arriving at the port. For this scenario, the duration of each port stay according to the given timetable is visualised in Figure 4. When selecting a port for increasing charging power, the potential energy gain per unit of added power is greater if the vessel's stay in that port is longer. In this example, in order to mitigate battery depletion before arrival in Tromsø, it may be more relevant to increase the size of the charger in Bodø than in

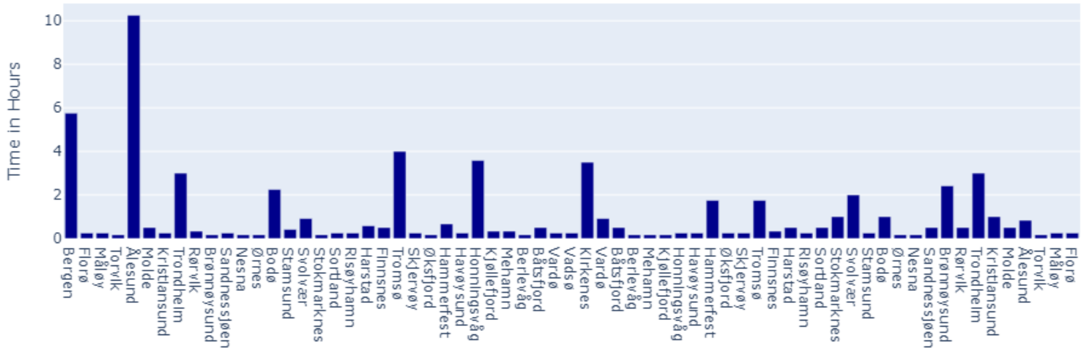


Figure 4: Duration of port stays according to the winter timetable.

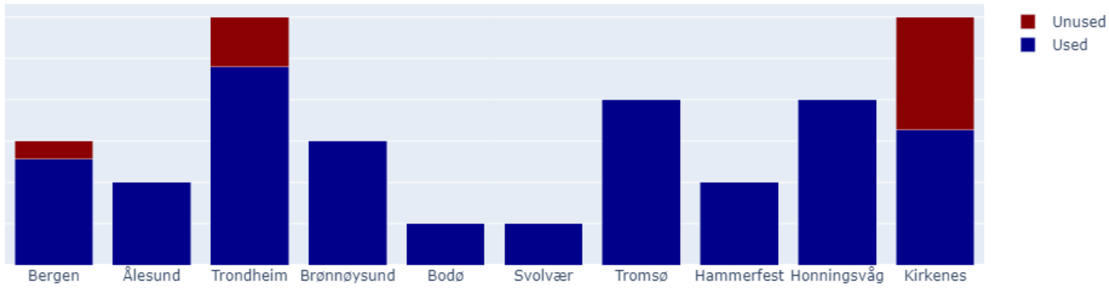


Figure 5: Installed charger power per port including the proportion of unused power (not utilised in any season during northbound and southbound journey).

Brønnøysund, where the duration of the northbound stay is significantly shorter.

Even though there is a sufficient amount of energy that can potentially be delivered from the charger during a port stay, it may not be possible to store the energy due to limited available capacity in the battery. In Figure 3, this becomes visible as horizontal parts of the figure at the battery capacity limit, for example during the northbound stay in Ålesund. As the majority of ports are visited twice, the SoC graph may not immediately reveal in which ports the installed power can be reduced without effecting the SoC. From the simulation data, we can calculate the power used in each port during the round trip. Figure 5 shows these numbers set up against the installed capacity. This information can be used to regulate charger size to the minimum power needed to achieve the same result.

For a broad overview of battery and charging infrastructure options for one timetable and energy demand, the ratio of battery-electric operation can be visualised against different battery capacities and total charger capacities. Figure 6 shows this for two different timetables with respective energy demands. Both plots show the same general pattern, highlighting two trends to be kept in mind when choosing battery capacity and charging infrastructure:

1. For a small onboard battery, increasing the charging power does not yield any significant improvements in the percentage of battery-electric operation. For increases in charging power to have an effect, the battery capacity needs to be big enough. The same applies vice versa: An increase in battery capacity only impacts the ratio if enough charging power is available.
2. The final increments in the percentage are the most costly to achieve: As the percentage increases, the additional battery capacity and charging infrastructure required for further improvements grow significantly (the distance between the traces indicating a 0.05 rise in the ratio is expanding towards the upper right corner), while initial increases can be achieved with relatively small additional investments.

Furthermore, the Charging Model can give hints on effective timetable changes. Typically, extending port stays to allow for more time to charge the battery may open for a decrease in charging power in the respective port. However, if there is a requirement on the overall trip length, extended port stays need to be balanced by either shortening the stay in other ports, or decreasing the time to sail certain legs, thus increasing the sailing speed. In the latter case, the trade-off between charging more energy during the port stay and using more energy to sail faster can be observed by simulating scenarios with different timetables and observing the change in SoC as well as the percentage of battery-electric operation.

For this case study, the port stay in Brønnøysund is an example for beneficial timetable changes: The southbound port stay in Brønnøysund is among the longer port stays, making Brønnøysund a candidate for charging infrastructure (see Figure 4). The northbound stay however is significantly shorter, allowing for very little charging, if any. Moreover, as discussed above, the northbound stretch from Trondheim

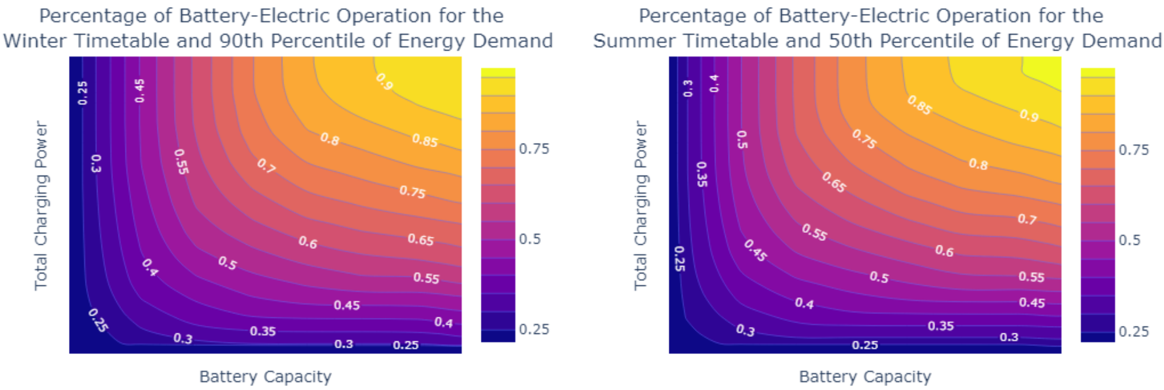


Figure 6: The percentage of battery-electric operation for different battery capacities and charging infrastructure options. The charging infrastructure options are characterized by the total installed charging power, i.e. the sum of the installed charging power in each port. The percentage plotted for each value of total installed charging capacity is the maximum percentage among all charging infrastructure options that amount to the same total installed charging power.

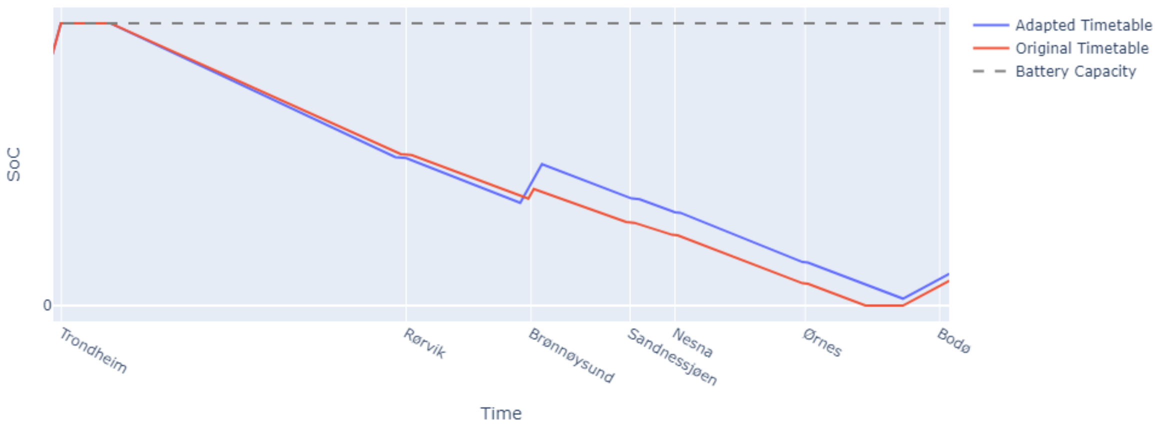


Figure 7: The change in state of charge (SoC) for the winter timetable and an adapted version.

to Bodø via Brønnøysund imposes a minimum limit to the battery capacity, as Figure 3 shows. Figure 7 compares the winter timetable with an adapted version as presented in Table 1. The extension of the stay in Brønnøysund is balanced out by shortening the sailing time for each of the three sailing legs before and after the port stay in Brønnøysund. Both departure from Trondheim port and arrival in Bodø port remain unchanged. As the slightly steeper decline in battery SoC for the adapted timetable in Figure 7 shows, the faster sailing speed does require more energy, but the extended charging time in Brønnøysund dominates the trade-off. The percentage of battery-electric operation between Trondheim and Bodø is 95.48% for the winter timetable and 100% for the adapted timetable, further illustrating the improvement.

To investigate how real-world delays and time deviations affect battery-electric operation for a given charging infrastructure and battery capacity, historic AIS data can be used as described in Section 2.3. As an example, Figure 8 illustrates the sensitivity of the arrival SoC with respect to actual delays. Late arrivals at Ålesund (northbound), Kirkenes (northbound), or Svolvær (southbound) can cause substantial deviations which require larger amounts of energy to be supplied from a backup energy source.

4 Discussion

As described in Section 2.1, the calculation of the energy demand is decoupled from the Charging Model and must be conducted independently before running the Charging Model. One benefit of this is reduced computation time for simulating different scenarios. While energy calculations may be time consuming, the polynomial input structure allows for efficient calculation of the energy demand depending on the timetable. Another advantage of this separation is modularity: both the Charging Model and any energy calculations can evolve independently without requiring changes to the other.

Table 1: Minor changes to the original timetable to optimize battery-electric operation.

	Original Timetable			Adapted Timetable	
	arriv.	depart.		arriv.	depart.
Trondheim	9:45	12:45	=	9:45	12:45
Rørvik	21:40	22:00	shifted 10 minutes	21:30	21:50
Brønnøysund	01:35	01:45	extended by 2 · 15 minutes	01:20	02:00
Sandnessjøen	04:35	04:50	shifted 10 minutes	04:45	05:00
Nesna	06:00	06:10	shifted 5 minutes	06:05	06:15
Ørnes	10:00	10:10	=	10:00	10:10

As the Charging Model accepts the energy demand data as a parameter, we are effectively choosing assumptions about the vessel and the sailing environment by selecting a certain dataset: both the vessel characteristics like size, systems, and design, and the weather including oceanographic parameters like waves, tides, and currents impact the energy demand of the vessel. Simulating the same scenario for different datasets therefore allows us to compare different technologies or different environments.

To effectively use the Charging Model for decision support in planning, it is crucial to define a goal for battery-electric operation. The Charging Model is best suited for a zero-emission goal set for all legs independently, i.e. sailing each leg with 100% of the energy supplied from the battery in 90% of the sailing conditions. As an alternative, a goal set for a complete journey requires a different model structure, taking into account dependencies between legs, at the expense of detailed control of where the alternative energy source is used. An approach as presented in this work is advantageous when there are different requirements for different legs, for example due to zero-emission policies in certain areas, as it is the case for the Geirangerfjord in the Coastal Express case.

While dependencies between the legs are not modelled explicitly in the Charging Model, during real-world operation, energy-demanding weather conditions for one sailing leg increase the likelihood of energy-demanding conditions for all sailing legs in proximity. Moreover, difficult sailing conditions may lead to cancelled port calls, changed sailing routes or timetables, and cascading delays. Defining the timetable as a parameter, presented methodology enables studying these effects by analysing the effect of different timetables.

The presented methodology focusses on exploring possible technical solutions for reaching different zero emission targets, as opposed to installation and operational expenses. Although they are of high importance, the uncertainty in such cost estimates is currently too substantial, because the charging concepts and the required investments in battery and charging infrastructure are still under investigation. This point extends to the possibility of sharing infrastructure usage and costs with other sea- or land-based transportation. It can, however, easily be extended to assign costs to different alternatives in the future.

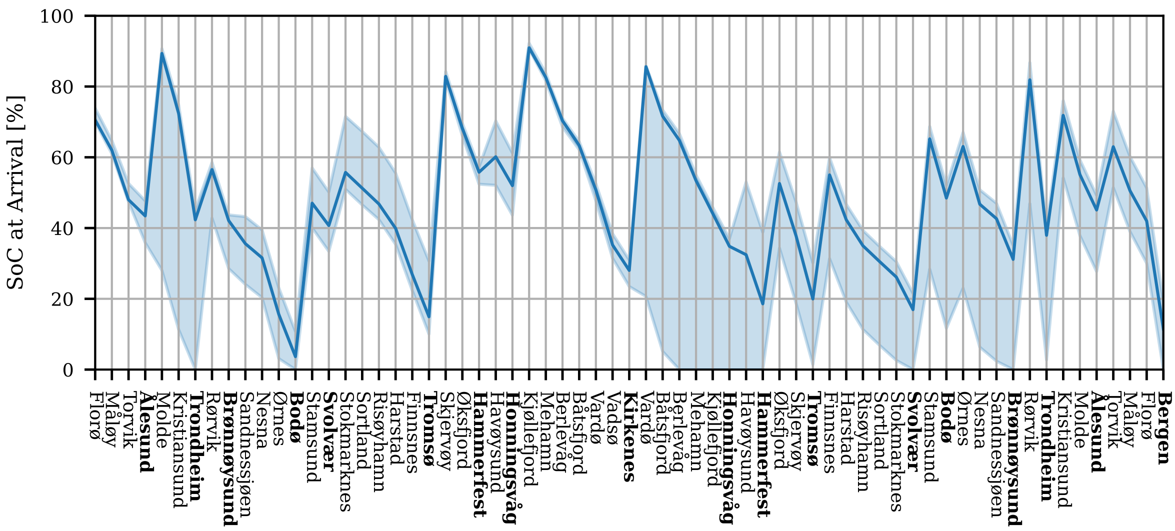


Figure 8: Range of simulated state of charge (SoC) values at port arrival during 22 complete round trips selected from the winter and spring seasons in the periods of 01.01.–31.05.2022 and 01.11.2022–31.05.2023 (light blue bands) compared to following the reference timetable without any deviation (dark blue line). The results shown stem from an exemplary energy demand scenario which would lead to 100 percent battery-electric operation had it not been for the variability in port arrival and departure times.

5 Conclusions

This paper has introduced a method for analysing different alternatives for charging infrastructures for battery-electric vessels. The presented parametrised model studies the expected percentage of battery-electric operation as influenced by onboard battery capacity, charger locations, charger power ratings, timetable, and stochastic energy demand caused by varying weather conditions and delays. Furthermore, the methodology has been demonstrated for the Norwegian Coastal Express, working towards zero-emission operation for large passenger vessels serving 34 ports along the Norwegian coast on a regular 11-day round trip.

Such "what-if" tools have proven useful to understand the consequences of different choices for battery sizing and charging infrastructure realization for a new generation of vessels serving the Norwegian Coastal Express route. However, the presented methodology is by no means restricted to this case, and we fully expect it to be useful for similar electrification projects.

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Jon Dæhlen received his B.Sc. in automation in 2011 and M.Sc. in engineering cybernetics in 2013. Since then, he has worked in software and control system engineering within the maritime sector. Initially, he contributed to a leading manufacturer of deck handling equipment, and since 2017, he has been with SINTEF Ocean. Currently a senior software developer, Jon's recent work focuses on developing software tools for naval architecture, particularly simulation solutions to estimate ship performance in logistic systems.