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Estimating the replacement potential of Norwegian high-speed passenger vessels with zero-emission solutions

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ABSTRACT

High-speed passenger vessels have high greenhouse gas emissions per passenger kilometre travelled and require optimizations to provide a role in a low carbon society. This article works towards this goal as a study of the potential for replacing high-speed passenger vessels with compressed hydrogen or battery electric zero emission solutions. To do this, a model was developed based on automatic identification system data to calculate energy use for the existing Norwegian fleet in 2018. Using modelled energy consumption and assuming a maximum battery weight or compressed hydrogen volume each vessel can carry, the most likely candidates for replacement were identified. Results showed that 51 out of 73 vessels are most suitable for hydrogen propulsion, with 12 also suitable for battery electric propulsion. However, timetable and route changes are required for more vessels to be suitable. Route optimisation studies are therefore required, along with further detailed feasibility studies of the identified candidates and infrastructure requirements.

1. Introduction

Greenhouse gas (GHG) emissions from maritime transport are projected to increase between 50% and 250% by 2050 under an unmitigated business-as-usual scenario (IMO 2014). To address this, the International Maritime Organisation (IMO) intends to reduce GHG emissions from shipping by at least 50% by 2050 compared to 2008 levels, and recommends research and development of low-carbon and zero carbon fuels for marine propulsion (IMO 2018). As of yet in Norway, a leading European zero-emission transport market, there are no binding emission targets for the maritime sector as a whole. However, it is planned by the Norwegian Government that all public transport should be fossil free by 2025, including ferries and high-speed passenger vessels (Norwegian Government 2019).

Uptake of zero-emission technology in the maritime sector has almost exclusively been related to propulsion deriving from electricity stored in batteries. The first fully electric car ferry, the MS Ampère, came in 2015 (Ship-technology 2021). As of 2019 there were 166 vessels (mostly car/passenger ferries) with batteries in operation worldwide, of which 34 were fully electric (DNV-GL 2019a). Fuel cells for maritime applications are also considered a solution for reducing emissions (van Biert et al. 2016), but few zero emission fuel cell vessels have been in operation. However, technology developments are progressing and the first liquid hydrogen driven ferry the

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MS Hydra was launched in 2020 (FuelCellWorks 2020). More zero-emission vessels are forthcoming worldwide, both for ferries and other segments (Fahnestock and Bingham 2021, Youd 2021). Since many ferries and passenger vessels are administrated by national and local authorities they are good candidates for green public procurement which can accelerate the transition (Ystmark Bjerkan et al. 2019). Even if zero-emission technologies for vessels are advancing there are challenges, for example related to on-shore infrastructure and energy availability(Ystmark Bjerkan et al. 2019), especially on islands (Pfeifer et al. 2020).

High-speed passenger vessels (service speed $\geq$ 20 knots) are prime candidates for replacement with zero-emission solutions since they are a transport mode with one of the highest GHG emissions per passenger km travelled. However, their usage profile is demanding with regards to power requirements and time for charging/bunkering, and to our knowledge there are currently no operating zero-emission services worldwide. The world's first hydrogen high-speed passenger vessel (22 kn) will be launched 2021 in the U.S (Water-Go-Round 2021), and the world's first fully electric high-speed passenger vessel is currently being developed in Norway (23 kn) and not expected before 2022 (Interreg Europe 2020).

Some studies have investigated feasibility of high-speed zero-emission passenger vessels for route operation. Generally speaking, these are either carried out fleet-wide using aggregated data with low level of certainty, or at a high level of detail for certain vessels (Pratt and Klebanoff 2016) or routes, and mostly derive from Norway. Annual diesel consumption for all scheduled Norwegian high speed passenger vessels in 2015 was estimated by Selfa Arctic (2016), which was subsequently used to determine the feasibility of two specific routes to zero-emission solutions. The Selfa Arctic (2016) estimates were consequently used as a basis for a hydrogen feasibility study by Hirth et al. (2017), who focused on hydrogen supply, quay facilities and safety, assuming a vessel design with 450 kg storage capacity, and by Aarskog and Danebergs (2020), who performed a zero-emission feasibility analysis for the fleet. In general results show that battery solutions are technically and economically feasible on shorter distances where charging opportunities are frequent and load variation is high, whilst hydrogen fuel cells are more suited to longer distances with increased energy demand.

More detailed feasibility studies for this segment, which may include vessel design and route modification assessments, are also commonly requested by municipalities or public transport authorities with an eye for the next tender round. Examples are to be found for several Norwegian counties (Brødrene, 2017, Flying Foil and Aa, 2019, LMG Marin 2019, Rødne 2019, Transportutvikling AS 2019, DNV-GL 2017, Buskerud Fylkeskommune et al. 2017, Øvrebø et al. 2019). Although providing in-depth technical solutions, findings of these studies cannot be directly transferred to other vessels or routes.

More widely, data provided by the automatic identification system (AIS) - an automatic tracking system deriving from transponders on vessels - can be used to compute vessel movements and provide a basis for detailed vessel or broad fleet analysis. This is most commonly utilized as a basis for energy and associated emission inventory modelling (Mjelde et al. 2014, Johansson et al. 2017, DNV-GL 2019b) route analysis (Fiorini et al. 2016, Mao et al., 2018) and collision risk (Mestl et al. 2016, Greig et al. 2020), but can also be applied for determining zero-emission technology feasibility. This approach was utilized by Aarskog et al. (2020) to determine the feasibility of replacing one high-speed passenger vessel to a similar one with hydrogen fuel cell propulsion. On a fleet level, Jafarzadeh and Schjølberg (2018) utilized AIS data to identify vessel types that can benefit from electric and hybrid propulsion through analysis of operational profiles. Their results showed that offshore and passenger vessels can potentially benefit from hybridization and electric concepts since they have dynamic operation profiles and spend a large amount of time under partial load away from diesel engine design conditions. High-speed passenger vessels were not specifically studied. Similarly, AIS data for three months in 2016 was utilized by Amundsen et al. (2018) to calculate energy consumption of Norwegian high-speed vessels per trip; by assuming that only vessels with a maximum energy consumption per trip of 1 000 kWh can be electrified, the potential for battery electric technology was

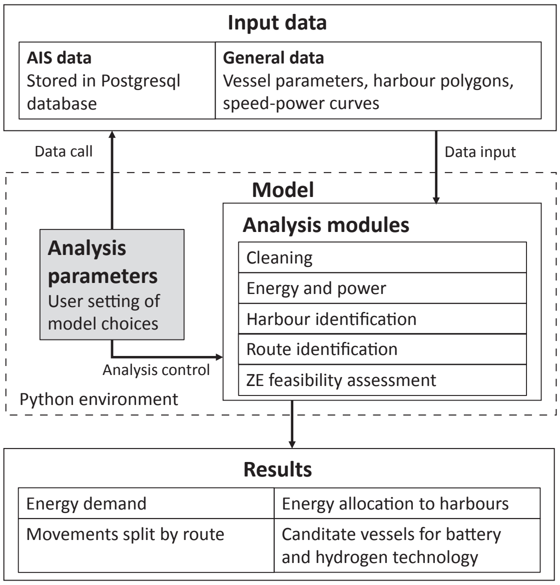

Fig. 1. Model overview.

studied. Benefits of these fleet-wide analyses based on AIS data is that they can be used for comprehensive screenings of replacement potential as a first step for detailed feasibility studies on identified suitable vessels/routes.

In this article we use AIS data to determine route requirements and energy demands of the high-speed passenger vessel fleet in Norway with the goal to estimate candidates for zero-emission replacement and possible energy needs at given locations. The novelty of our approach lies in the combination of multiple levels of detail; use of AIS data allows for disaggregated analysis at a route level and identification of charging and bunkering potential based on actual movement patterns, whilst the use of wider feasibility assumptions allows for a fleet-wide automatic analysis. To our knowledge, this is also the first published study applying a full year of AIS data to determine zero-emission feasibility in the fleet-wide high-speed passenger segment. The analysis does not consider optimizations that would be made with technology shifts or more specific on-board arrangements, but results can be used as a crucial first step in a more detailed chain of feasibility studies.

2. Materials and methods

For this work we developed a model that calculates the distribution of energy demand for each high-speed passenger vessel in Norway based on individual vessel movements, using AIS data for the year 2018. From this basis the model then considered which routes and vessels are best suited for each zero-emission solution, accounting for the quantity of compressed hydrogen or weight of battery system vessels of each size can potentially store/carry and time available at harbours for bunkering or charging. The model is developed in python using common libraries (including e.g. Pandas, NumPy, SciPy, Folium and Scikit-learn).

A general model overview is given in Fig. 1, with a summary of all model parameters and assumptions given in Table 1, and described further below.

2.1. Data preparation and movement splitting

A list of Norwegian high-speed passenger craft by Maritime Mobile Service Identity (MMSI) number, together with associated vessel properties, was obtained from MarineTraffic (2019). To do this, a filter search was used to obtain vessels that are 1) sailing under Norwegian flag, 2) of high-speed type, and 3) passenger carrying. Together, 81 vessels fulfilled these criteria.

AIS data for these vessels was obtained where possible from the Norwegian Coastal Administration (NCA), covering 74 vessels for the year 2018. One vessel did not have data coverage for much of the year and was excluded from further analysis. Additional vessel parameters including hull design and service speeds were obtained from publicly available sources, including Norled (2020), Brødrene Aa (2020), Skipsrevyen (2020), Skipsarkiv Rogaland (2020) and Servogear (2020). Most vessels are catamarans with mainly waterjets for the newer vessels and propellers for the older vessels. An overview of other vessel characteristics is given in Table 2, with Fig. 2 showing a selection of the AIS dataset revealing the geographic coverage of the high-speed vessels.

The AIS dataset had readings down to 1 s time resolution, containing up to 7 million records for one vessel over the full year. The data was cleaned and downsized in sequential steps in the model. Duplicates in time were removed first, along with sequential duplicates in space (lat/lon). The number of sequential speed over ground datapoints (SOG) equal to zero was reduced by keeping the first and last record. Non-available SOG readings were either replaced with calculated velocity (using distance travelled and time intervals between records) if the calculated velocities were lower than the maximum speed known for each vessel, or discarded. When the vessels were registered as moving some records were discarded when they were considered as outliers with time (delta t) between records being too high. These were consequently treated as holes in the dataset. An overview of the data for the included vessels, before and after cleaning, can be found in Table 3.

Analysis was performed using model parameter values set equal for all vessels, based on general behaviour patterns coupled with a

Table 1
Summary of primary input parameters used in the model.

Parameters			Value
Data preparation and movement splitting	Harbour identification	Maximum speed for harbour identification (knot)	1.5
		Defined radius of harbour clusters (km)	0.5
	Trip finding	Maximum velocity for trip finding (knot)	2
		Maximum distance for a vessel to be considered ‘at harbour’ (m)	50
Fuel use	Diesel Assumptions	Diesel lower heating value (kWh/kg)	11.86
		Average diesel engine efficiency (%)	37
Zero-emission feasibility	Battery assumptions	Maximum depth of battery discharge (%)	60
		Assumed battery energy density (kg/kWh)	8
		Estimated maximum battery weight per vessel (% of DWT)	80
		Maximum available charging power (MW)	10
	Hydrogen assumptions	Hydrogen lower heating value (kWh/kg)	33.3
		Average fuel cell efficiency (%)	50
		Estimated maximum hydrogen weight per vessel	Scaled from the MS Sylvarnes (450 kg), using area
		Estimated bunkering time (min/450 kg H_2)	20

Table 2
Overview of the characteristics of the vessel sample.

	Engine power (kW)	Max Speed (kn)	Length (m)	Width (m)	Built year	DWT(t)	PAX
Median	1498	32	27	9	2008	22	147
Min	700	20	20	6	1975	7	42
Max	4640	38	41	12	2017	125	296

Fig. 2. Geographic coverage of AIS dataset. A section showing route level detail is given in the excerpt.

sensitivity analysis to select appropriate values. Harbour areas were identified by isolating coordinates where SOG < 1.5 knots, and applying a clustering algorithm (DBSCAN) (Boeing 2018) to group data into clusters with radius < 0.5. Although in practice the vessels are stationary when at harbours for passenger embarking/disembarking, due to data coverage and AIS accuracy, low speeds (<1.5 knots) were used for this instead. Midpoints of the clusters were compared with polygons obtained from the NCA containing all recognised harbours/quays in Norway for identification and naming of harbour locations. As part of this step, locations where the vessel was stationary or with low speed, but that are not classified as harbours by the NCA, were screened out. The navigational status component of the AIS dataset (where a 'moored' status can be registered) was not used for harbour identification purposes since it was found to be inconsistent between vessels. Additionally, it is not used for short stops by the vessels along their routes which are of interest in this study.

To identify movement patterns between harbours, records in the dataset where SOG < 2.5 knots were isolated and the distance to identified harbours was calculated for each vessel. Data points where distance to a harbour were less than a set distance (<0.5 km) were flagged with this harbour's number, which we designated arbitrarily. From this we obtained patterns of harbour visits, as well as

Table 3
Description of AIS data and impact of the data cleaning and downsizing.

Dataset descriptor		Per vessel statistic, by percentile		
		25%	50%	75%
Dataset time coverage (d)	Before cleaning	365	365	365
	After cleaning, corresponding to vessel activity coverage	334	346	357
Dataset length (number of records)	Before cleaning	2,219,701	3,920,193	5,037,055
	After cleaning	1,483,536	2,454,441	3,412,475
Median time between records (s)	After cleaning	3	3	3
Speed	Unavailable SOG before cleaning	0	7	40
	Number of records cleaned away due to high SOG/velocity	0	1	5
	Number of SOG = 0 removed	103,224	178,532	301,676
Dataset duplicates	Number of spatial duplicates removed	388,445	654,016	1,009,721
	Number of temporal duplicates removed	22,312	37,952	63,229

identifying the times arriving and leaving each harbour throughout the year. Later, harbour numbers were re-matched with each harbour name from NCA. An example is given in Fig. 3, which also corresponds well to the timetabled movements from the operator for year 2018 (T. Nørbech, personal communication, 5 May 2020).

The vessel movements were divided into trips between two or more harbours based on a cut-off for duration at harbour (Fig. 4); this time cut-off can be set as one wishes in the model for each vessel. The reason for this is that the time needed at harbours for charging or bunkering will set limitations for the feasibility of zero-emission vessels while at the same time keeping the current service level. Trips with the same harbour movements pattern were thereafter grouped as a route. The timetabled routes by vessel service operators typically vary over the week with different harbour stops during weekends or with stops only served when travellers indicate the need. Defining routes based on exact harbour visit patterns will hence typically give several routes with the same start and end harbour for one vessel. Another consequence of defining routes as we do in the model is that the same harbours could be visited several times in one identified ‘route’ if a large time cut-off is set.

An example of the distribution of route lengths for two vessels (MS Terningen and MS Tyrhaug) that operate on the same service between Trondheim and Kristiansund is shown in Fig. 5. For demonstration purposes, two cut-off times of 10 and 30 min were used in Fig. 5a and Fig. 5b, respectively. In each case, the major peak corresponds well to the distance between end-stops of between 92.5 and 95.0 nautical miles (Hirth et al. 2017), or around 175 km. With a cut-off of 30 min (Fig. 5b), the main difference is the presence of an additional peak at ~ 360 km that likely corresponds to a full return journey. Checking of the timetable supports this theory, since in in some cases the stopover at Kristiansund is only 20 min (i.e. not long enough to ‘trigger’ a new trip in this case).

2.2. Energy demand estimation

The energy demand for propulsion was calculated for the high-speed passenger-vessels in two ways. Speed-power curves were obtained and applied for 30 vessels in the national fleet from Brødrene Aa, a leading Norwegian manufacturer of high-speed vessels. For the remaining vessels, energy demand was calculated using a general model widely applied in similar studies (Goldworthy and Goldworthy 2015, Jafarzadeh and Schjølberg 2018), according to Equation (1). Here LF is the engine load factor, P and P_{max} are respectively the current and maximum engine power output, $u_{1,2,}$ u_{max} and u_{ss} are respectively the vessel’s current, maximum and service speeds and f is a fraction of the maximum engine power used at a vessel’s service speed it is designed for. Although in many studies f is taken to equal 0.83, this is a generic value used for multiple vessel types. The function is not developed for high-speed

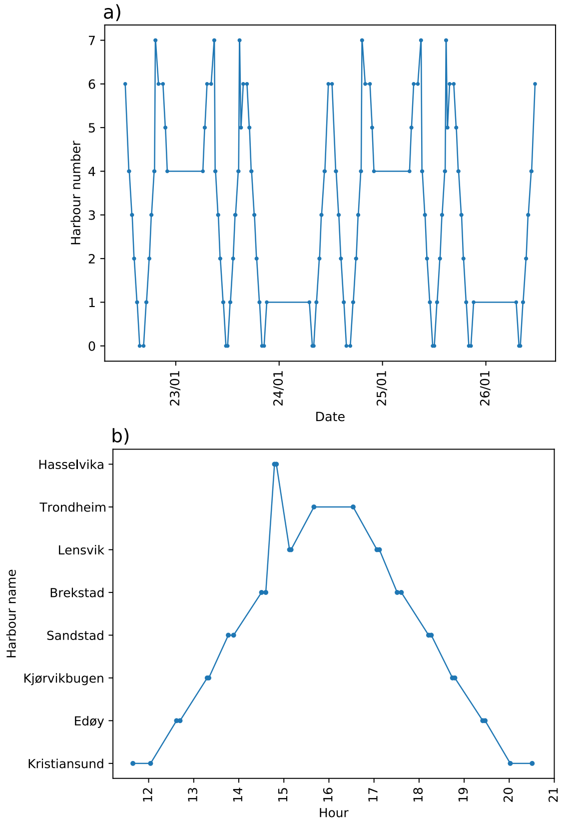

Fig. 3. Example movements between harbours for the MS Terningen over a) a four-day period and b) one afternoon (23/01) in January 2018 Note: harbour numbers are arbitrary.

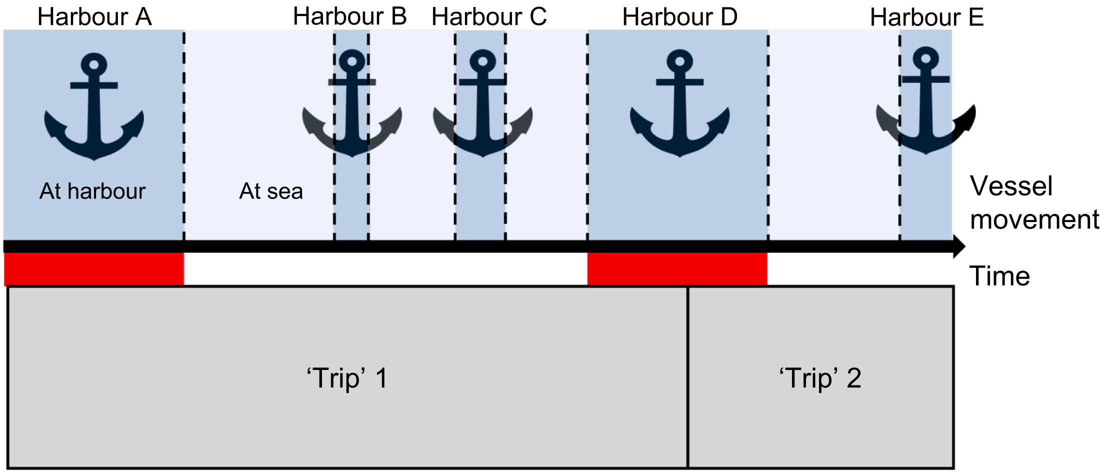

Fig. 4. Definition of 'trip' in this study, relative to a harbour stay duration cut-off time applied in the model. The red bars represent harbour stays where time >cut-off, triggering a new trip to be registered. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

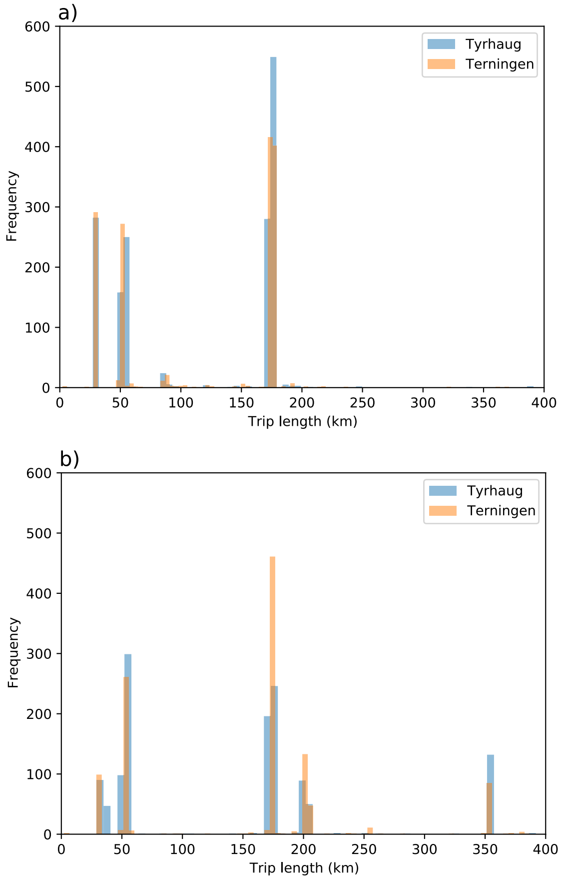

Fig. 5. Example trip length distribution identified with the method for two vessels that serve the 805 Trondheim-Kristiansund connection in Trøndelag, the MS Terningen (orange bars) and Tyrhaug (blue bars). Movements were divided into trips using time at harbour, using cut-offs of a) 10 and b) 30 min. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

passenger vessels and is thus expected to underestimate the energy demand. Therefore, we did a comparison for the Brødrene AA vessels using both the given power curves and Equation (1) with $f = 0.83$. The differences found for the total yearly energy was then used as a scaling factor of 1.24 to calibrate the results.

$$LF = \frac{P}{P_{max}} = \left(\frac{u_{1,2}}{u_{max}}\right)^3 = f\left(\frac{u_{1,2}}{u_{ss}}\right)^3 \tag{1}$$

The power was then multiplied with time to obtain the energy demand, assuming constant power across the time intervals (delta t).

From the energy demand one can then estimate the needed fuel using the lower heating value (LHV) and the engine efficiency (see the example for hydrogen in section 2.3). Note also that as Equation (1) links the power of the engine with the speed of the vessel, all losses of energy after the engine such as in the transmission system (gear, shaft, propeller, etc.), are included. This is also the case for the speed power information given by Brødrene AA.

Relatively low energy use derives from auxiliary and hotel loads during transit periods of high speed vessels (3–4%), due to the high energy consumption by the propulsion systems (LMG Marin, 2016, Francis 2019). Furthermore, these loads have an energy efficiency improvement potential. Due to their small impact on the total system during transit, potential to satisfy this demand in harbours with onshore power and the general character of this study, the auxiliary and hotel loads are thus neglected here.

2.3. *Zero-emission feasibility criteria*

To identify which vessels are potentially feasible to be replaced with zero-emission vessels of similar size, or convert to zero-emission technologies, we made a set of assumptions for the dimensioning of the zero-emission system. It is foreseen that all zero-emission vessels will be new-builds, but we assumed here for the initial screening that the general size and energy demands are comparable with the current fleet, or at least scalable with future needs. Hence, we use the current energy use of the vessels as representative for the identification of the vessels (and routes) most likely to be feasible.

When considering battery capacity, a Depth of Discharge (DoD) of 60% was set as a limit since a large DoD notably reduces battery lifetime (Ecker et al. 2014) and a need for safety margin on battery size to manage unforeseen events. The battery weight density is based on the Corvus Dolphin Power battery (8 kg/kWh) (Corvus Energy 2020). The maximum battery capacity for each vessel was estimated by assuming an upper limit of battery weight corresponds to 80% of the vessel's dead weight tonnage (DWT), as in Aarskog et al. (2020). DWT is an accessible parameter of existing vessels and in this case is used as a simplified proxy to estimate max carrying capacity of batteries for a similar size and type of vessel. The methodology was presented to several maritime actors and ship builders, and agreed on as a reasonable simplified approach. Due to uncertainties connected to this approach, sensitivity testing has been included of this parameter in section 2.4.1. We also assume for simplicity that the batteries and the electric engine are 100% efficient. We then set the available charging capacity onshore to be 10 MW, which allows the theoretical time needed to fully charge the batteries in between trips to be calculated. 10 MW represents the higher end of charging powers that have been used to date, and leads to an optimistic approach that will give what we consider the lowest charging times possible. The found charging times, unique for each vessel, were primarily used as the cut-off time in the model (as described in section 2.1) for identifying the battery feasible trips.

Estimated hydrogen requirements (kg), assuming replacement with hydrogen electric propulsion, were calculated from energy demand estimates using the hydrogen LHV of 33.3 kWh/kg, and an estimated average fuel cell efficiency of 50% (Aarskog and Danebergs 2020). The theoretical maximum compressed hydrogen storage capacity per vessel was then calculated assuming that capacity is limited by volume and needs to be located on open deck due to safety, and is thereby dependent on the deck area. The hydrogen powered high-speed vessel concept GKP7H2 within the Norwegian public–private cooperation "Green shipping program" was used as a reference case for this (Nygård and Strømgren 2017). This concept vessel is based on a Brødrene AA design with the aim to replace an existing vessel in operation, the MS Sylvarnes, and is equipped with three tanks of compressed hydrogen at 250 bar (150 kg each); i.e. a total storage capacity of 450 kg hydrogen. In this study it is assumed close to maximum storage capacity for the given vessel size. We then estimated the maximum hydrogen storage capacity for other vessels by scaling on approximate deck area from the known vessel lengths and widths. The theoretical time needed to fully bunker with hydrogen in between routes was calculated by allowing 20 min per 450 kg hydrogen, which was found to be within reach using two nozzles (Hirth et al. 2017) plus an extra 10 min to allow for the fact that bunkering locations are likely to be outside of central harbour areas where passengers embark/disembark. As before, the found bunkering times for each vessel were primarily used as the cut-off times in the model for identifying the hydrogen feasible routes. Additional analysis was also carried out to investigate feasibility assuming hydrogen bunkering per day rather than between trips.

Vessels most suitable to battery or compressed hydrogen electric propulsion technology were then identified by assuming that a solution is possible if it covers energy demands for more than 90% of activity.

2.4. *Model uncertainties and sensitivities*

Uncertainties in the modelling relate to 1) the methods and assumptions used, 2) the quality of the input AIS data itself, and 3) the completeness of the AIS data when discussing energy use of the 'fleet'. For the latter, Norwegian Government (2019) indicate that 74 high-speed passenger vessels with AIS were active in 2017, which is the same as the numbers of vessels we identify in 2018. There are also high-speed vessels in Norway that are too small for AIS to be mandatory (Norwegian Government 2019), which are not covered in this study.

Uncertainty related to the AIS data includes precision in the geographic position and time intervals between data transmitted, with AIS quality known to vary between vessels. The cleaning before analysis is expected to limit these effects on final results.

More pressing are the effects of the method itself and model assumptions. For example, parameters defined for trip finding and harbour identification (specified SOGs, cluster radius, and distances from harbour) affect the number of harbours and visits identified. Where the velocity for trip finding was < 1.5 knots, the model was limited by the amount of data for trip identification. Additionally, when the specified cluster radius for harbour identification was very low, quay level stops were identified rather than general harbour areas, but when it was too high, harbour areas were merged together. The model parameters used thus reflect the best trade-offs available. For the harbour clustering there is also a risk that the clusters may fall outside the polygon areas if they are small, as the method takes the middle point of the records used for identification. In addition, we have no way of verifying the purpose of a harbour visit, and separating stops where passengers can embark/disembark from other stops for sightseeing/cruise activity/services is not possible. We performed a visual inspection of all harbours and polygons identified and found few obvious errors, but since the goal was to develop a generic method for all vessels it was important to limit vessel specific adjustments.

Regarding uncertainty of energy demand estimations; firstly, the function found in the literature, and applied in our model for energy calculations, was not developed for use on high-speed vessels. The function includes the cube of the speeds making it also vulnerable to possible errors in the service speeds registered. We scaled the needed energy for all vessels according to the speed-power curve data received from Brødrene Aa, which improves energy estimates compared to only using the function from literature. The standard deviation of the scaling factor for the selected vessels was 0.33. The deviation (using Equation (1) compared to the speed-power curves) was found to be smaller for trips with higher speeds where the main energy consumption occurs. Hence, the deviation will not only vary from vessel to vessel, but also from trip to trip. We do however not consider it appropriate to scale or correct on a more detailed level with the current information. Weather, currents, wave and wind conditions are also not considered in the model, which are known to affect energy consumption.

When considering zero-emission feasibility, the underlying assumption that energy demands will remain similar when vessels are replaced with zero-emission solutions is questionable. It is known that vessel optimisation and changes to vessel weight will affect energy demand, but we assume here that even if the overall energy efficiency will change, characteristics related to vessel size and routes operated will make energy needs scalable to future needs. Additionally, the feasibility assumptions themselves are related to technology and dimensioning of the systems based on current knowledge and concepts available. Future technology development will alter the feasibility results to likely include a higher number of routes/vessels. Available onshore infrastructure also sets limitations on the feasibility of zero-emission solutions. This article does not address power availability in the electricity grid at the harbour locations, nor the possibilities for hydrogen refuelling facilities and distribution pathways.

2.4.1. Effects of changes in the feasibility model assumptions

To determine the sensitivity of the feasibility assessment results to model assumptions, we performed a simple analysis by varying factors related to time needed to charge or refuel, as well as the carrying/storage capacity for batteries and compressed hydrogen. In our study these parameters are the constraints for the maximum energy that is available to each vessel for a trip.

The assumptions we used for the main results are rather crude as we do not have many example-vessels to base our assumptions on. Hence, testing the effect of changes in these assumptions will also give some insight to the possible challenges of zero emission solution replacement. As we set the charging power and refuelling times to an optimistic level in the main analysis, in the sensitivity analysis we only make these factors more conservative. In practice this equates to variation of charging power between 5 and 10 MW and variation of refuelling time between 20 and 40 min for 450 kg hydrogen. For the storage capacities we include a ± 20% of the initial values used, meaning approximate weight of batteries in the range of 65–96% DWT and a quantity compressed hydrogen storage per area in the

Table 4

Overview of key findings across the fleet relating to vessel movements and energy demand in 2018, and potential zero-emission feasibility. Note: the most popular route was defined here with a fixed harbour duration cut-off of 15 min for comparability of all vessels.

Parameter		Vessel statistic, by percentile		
		25%	50%	75%
Vessel movements	Number of recognised harbours visited in year	12	20	35
	Time per harbour stop (min)	1.5	3.0	8.0
	Distance covered by all routes (km)	34,058	64,103	91,162
	Distance of most popular route (km)	30	65	98
Energy demand	Median energy demand per day (MWh)	2.5	4.9	8.3
	Energy demand per year (GWh)	0.9	1.6	2.8
	Energy demand of most popular route (MWh)	0.5	1.3	2.6
	Estimated maximum battery size permitted (MWh)	1.9	2.2	3.3
	Estimated maximum hydrogen storage permitted (kg)	431	515	727

		Number of replacement feasible vessels identified	
		Battery	Hydrogen
Zero-emission feasibility	Vessels with 90% of movements (distance) covered	12	51
	Vessels with 90% of movements (routes) covered	18	61
	Number of vessels with 90% of days covered	–	41

range 1.85–2.55 kg/m^2. For batteries we include the change in total storage capacity as a change related to the DWT, but this could equally represent a change in the weight of the battery per kWh or more weight for other equipment. The feasibility is also affected by the time cut-offs used for each vessel. Hence, to see the effect of changing the general parameters, we used fixed time cut-offs to split movements into trips for all boats in this analysis. The time cut-offs were set to 5 and 10 min for the battery feasibility and 100 and 200 min for the hydrogen feasibility case.

3. Results and discussion

An overview of the key findings with regards to energy demand and potential feasibility of zero-emission replacement is given in Table 4. Describing vessel movements is not the main focus of the study, but a brief description of these is also included in the table as background to main results. A full overview with more details of individual results per vessel can be given by contacting the corresponding author.

3.1. Energy demand estimates

For the high-speed passenger vessels in our analysis, we calculate a total annual energy demand (output from the engine) of 151 GWh for the year 2018. We unfortunately do not have diesel consumption available for 2018 to verify this result. For a soundness check we therefore compared with Aarskog and Danebergs (2020) who estimate a total of around 200 GWh for 96 routes by the Norwegian passenger vessel fleet, based on the diesel estimates per route given by Selfa Arctic (2016). However, the number of vessels and number of routes in the studies are not directly comparable. The Aarskog and Danebergs (2020) study includes some routes also served by vessels with rated speed<20 knots, which are not included here. When removing these vessels from their estimates we get 174 GWh. We can therefore conclude that the two energy estimates compare reasonably well.

Daily energy demands per vessel, as well as the distribution of energy demands per day of the week, and per month, are shown in

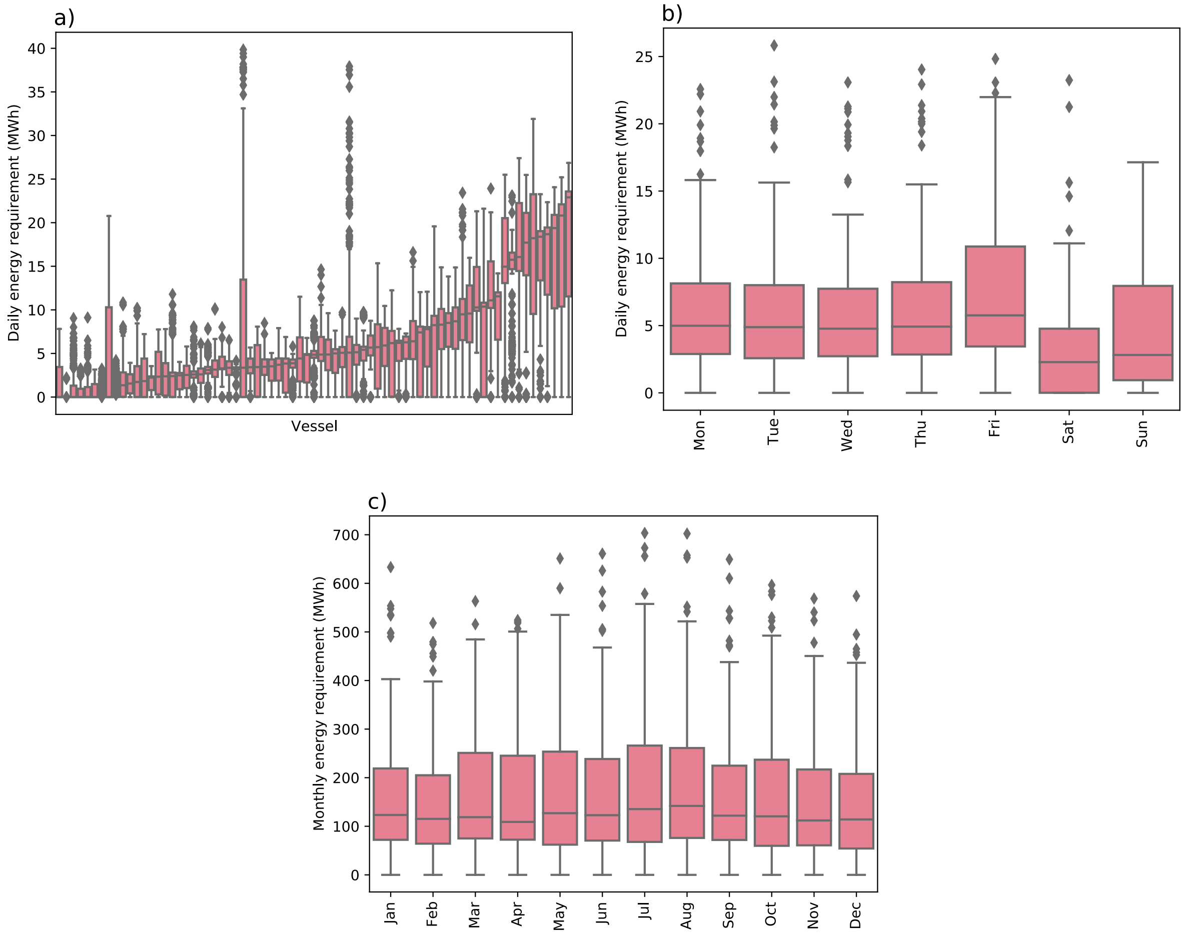

Fig. 6. Box and whisker plots showing a) daily energy demand per vessel, b) variation of energy demand per day of the week, and c) variation of energy demand per month of the year, during 2018.

Fig. 6. The daily energy demand per vessel varied widely, but the median daily energy demand across the fleet was around 5 MWh. As expected, energy demand has a clear weekday vs. weekend pattern with lower energy demand especially on Saturdays, corresponding to changes in timetabled activity. Monthly energy demand per vessel across the year seems rather constant, although with a small trend of higher energy demand in the summer months. Analysis showed that there were more vessels active in the summer and the total distance travelled by all vessels was about 30% higher in August compared to December. This is also reflected in the total energy demand.

Since the model does not take into account changes to weather and sea conditions, underlying movement patterns across the year were examined further, assuming that rough seas and wind are more prominent during some parts of the year that may result in reduced speed or changed routes. When selecting only vessels with data for all months (55 vessels) no overall seasonal trend in changes in speed compared to distance travelled was found; small variation can be seen for some vessels, but no conclusion can be made of the cause. This is a topic that could be explored in further studies by coupling with weather data, and also calls for better energy modelling tools for this vessel segment.

Energy demand was further disaggregated on a per route and per harbour basis. Each vessel has multiple routes that it undertakes throughout a year. With a cut-off harbour visit time between routes of 15 min, the median most popular route length for the vessels was 65 km (associated energy demand of 1.3 MWh). As well as expected variation in timetabled trip distances, major variations in route distance likely correspond to other trip purposes, such as for maintenance. As expected, certain routes are more frequent than others for one vessel, corresponding to main timetabled routes with no deviation.

In general, the harbour visit duration time for all vessels was short, with a median of three minutes. These short stops reflect the “bus-stop” function for most of the harbours, see also Table 4. However, high variation in harbour visit duration was found, with a maximum stay at harbour of 335 days for one vessel. These variations again reflect differences in harbour visit purpose, such as for allowing passenger disembarking/embarking, wait time between scheduled trips or harbour visits for maintenance or downtime.

Fig. 7 shows the aggregated total energy allocated to each harbour, where daily energy demand of each vessel throughout the year has been allocated to the harbour where each vessel had the longest stay on each day. The total here represents the cumulative energy demand for all days and for all vessels in the fleet. Analysis showed that 76% of these harbour stops occurred between 0000 h and 0900 h (as defined by the leaving time), representing the most common downtime period between timetabled days. Harbours that together reflect around 50% of the total energy of the fleet are shown in Table 5. The results show major hubs for energy demand in large cities such as Bergen, Stavanger and Trondheim, but also large amounts of energy allocated to islands and more remote places such as Skånevik near Bergen. In practise we expect that covering this energy demand at some places can be a challenge either due to practicalities or costs, making this important to explore as future work.

3.2. Zero-emission feasibility

Fig. 8 shows the percentage of each vessel’s movements that can be covered by battery and hydrogen electric propulsion, using annual distance and trips covered as indicators. These results were calculated using the movement patterns identified for each vessel

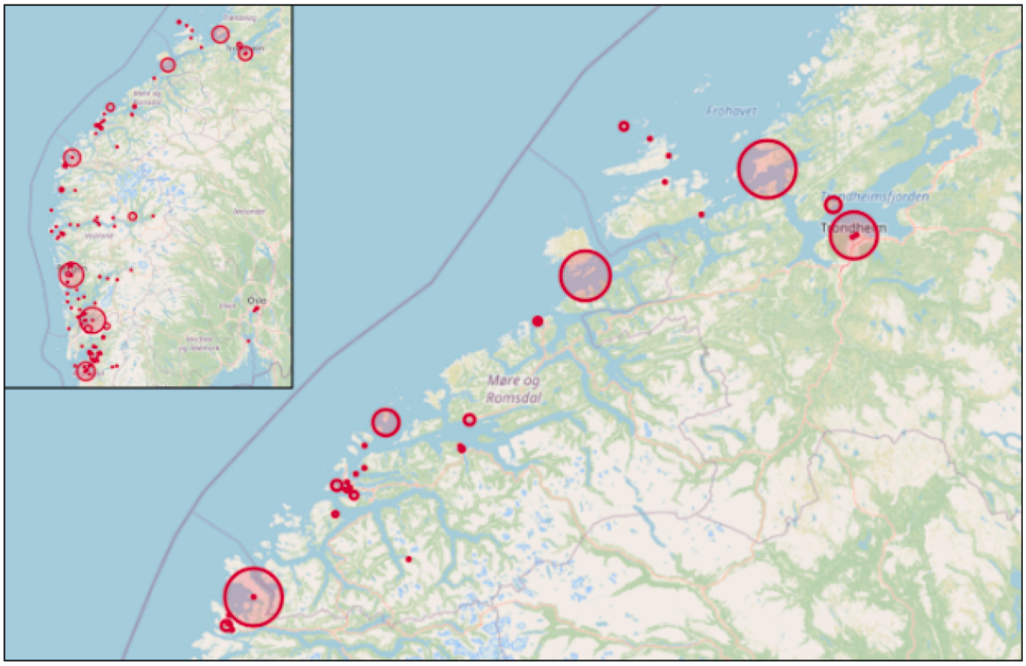

Fig. 7. Allocation of cumulative daily energy demand across all vessels to harbours, based on longest harbour visits per day.

Table 5
Allocated energy demand to harbours, that together reflect around 50% of total fleet energy demand. Inhabitants numbers are rounded to the nearest hundred.

Harbour name	Allocated energy demand (% annual total)	Harbour location (inhabitants)
Skånevik, Etne	7.7	Town (600)
Strandkaien, Bergen	7.1	City (260 000)
Østre havn, Stavanger	5.2	City (143 700)
Holmen, Sandnessjøen	5.0	Town (6 100)
Seljevågen, Selje	4.7	Town (2 800)
Sjøgata, Harstad	4.5	Town (24 700)
Sjøgata 5A, Tromsø¸	4.3	City (71 600)
Brekstad, Ørland	4.1	Town (2 300)
Brattørkaia 16–17, Trondheim	3.6	City (205 200)

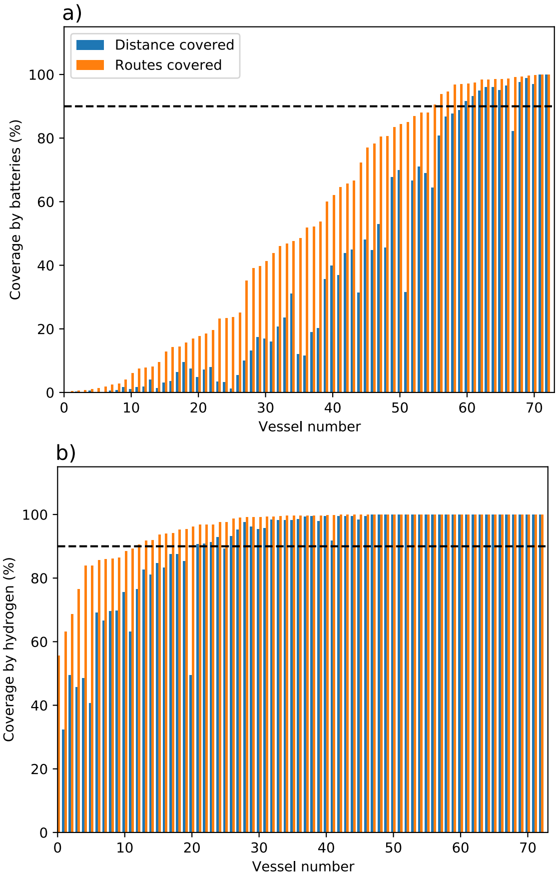

Fig. 8. Estimated feasibility as a basis of distance and trips covered for a) battery and b) hydrogen propulsion technology. The line indicates the 90% coverage threshold used in this analysis as suitability criteria.

and assuming bunkering and charging occurs in between each trip. For this analysis the movements were thus first split into trips using the time needed for full charging or bunkering, given the maximum battery or hydrogen storage capacity calculated for each vessel, and assuming a vessel is feasible for replacement if over 90% of its movements have an energy requirement within the maximum battery size or hydrogen storage defined for that vessel. Overall, 12 vessels were deemed suitable for replacement with battery electric propulsion, and 51 vessels were deemed suitable for replacement with hydrogen electric propulsion, when using the annual distance covered. The latter also includes the battery suitable vessels. Together these vessels are respectively responsible for 10 and 90 GWh of the annual energy demand across the fleet. 22 vessels were identified as not suitable for either battery or hydrogen propulsion, and responsible for 61 GWh of the annual energy demand. Maybe other decarbonising technologies, such as using liquefied hydrogen or ammonia fuel, could be a solution for these vessels, but are not investigated here.

Some trips are very long and have a higher weighting on results when distance is considered. When the number of trips covered was selected as an indicator rather than distance, a higher number of vessels were identified as candidates for battery or hydrogen technology (18 and 61, respectively).

For potential replacement with compressed hydrogen, bunkering on a per day basis rather than in between trips was also considered, which is a likely scenario due to the longer travel distances achievable with the stored hydrogen. According to these results, 41 vessels had over 90% of their days covered if fuelling with hydrogen once per day, responsible for 39 GWh of annual energy demand. The median hydrogen demand for these vessels per day, based on their energy requirements, was 201 kg (cumulatively, an annual total of 2400 t).

Table 6 shows the distribution of energy and hydrogen demand per harbour for the identified feasible vessels, where allocation of hydrogen is based on bunkering once per day (at the harbour with the longest stay for that day) and allocation of battery energy assumes charging between trips. These results can provide a potential guide to needed infrastructure. The model can also be applied in future work to look at harbours' energy need in more detail with higher time resolution.

Further analysis was performed to investigate underlying factors to the observed differences in replacement feasibility (Fig. 9). The analysis showed that in general, vessels that commonly serve very short routes, with a high percentage of short trips (e.g. < 50 km), are more suited to battery propulsion power, whilst those with longer routes are more suited to hydrogen propulsion power. This is similar to findings from other studies (Brødrene, 2017, Aarskog and Danebergs 2020). Smaller vessels (in terms of passenger numbers, PAX, or motor power) were also more likely to be identified as suitable for battery propulsion power rather than hydrogen. One outlier demonstrates that e.g. large vessels with respect to PAX and motor power might also be suitable for battery propulsion, if they serve short routes. Some vessels, which are also part of the passenger vessel service in Norway, are not included in this study because they are too small, or have rated speed<20 knots, such that AIS is not mandatory. However, our findings indicate that these smaller vessels may also be good candidates for zero-emission propulsion. Improvements in energy efficiency with zero-emission new build designs are expected to be significant (Brødrene, 2017). Results are thus not intended as a definitive guide to which vessels are optimum for zero-emission replacement, but rather indicate - based on historical energy demand - which vessels can be considered as likely candidates.

3.3. Feasibility results comparison

Comparing our feasibility results is not directly straightforward, since we take a vessel-based approach whilst most other studies in the literature are performed at a singular route level. Feasibility results at a route level from individual vessels were thus pulled out for more detailed comparison with other studies, focusing on the Trøndelag region. However, it is important to note that route level analysis provides only a feasibility snapshot based on one type of trip for a vessel and lacks the strength of a vessel-wide analysis.

Three key routes are discussed in Trøndelag. Most studies conclude that the Trondheim-Vanvikan route is suitable for battery propulsion (Brødrene, 2017, Flying Foil et al. 2019, Transportutvikling AS 2019), whilst the longer Trondheim-Kristiansund route is more suitable for hydrogen propulsion (Brødrene, 2017, Hirth et al. 2017). For the Trondheim-Brekstad route, some studies conclude it is suitable for hydrogen propulsion (Brødrene, 2017) whilst others conclude it is possible for battery propulsion (Transportutvikling AS 2019). Others conclude all routes are suitable for battery propulsion if an energy efficient hydrofoil is used (Flying Foil et al. 2019), or if battery swapping occurs for the longest routes (Transportutvikling AS 2019).

When we isolate the feasibility results for these routes from the four vessels (MS Terningen, Tyrhaug, Trondheimsfjord I and Trondheimsfjord II) that serve them, in keeping with the findings of many of these studies we find that with all vessels the Trondheim-Vanvikan route is suitable for battery propulsion since the energy demand is well within the maximum battery size estimated for the vessels. For the Trondheim-Kristiansund route, we find energy needs exceeding the battery size of the vessels, but that are within the hydrogen storage capacity of the vessels, that make hydrogen a suitable propulsion technology in all cases. For the Trondheim-Brekstad route, we find that the route can be served by battery power, although the energy demand is nearing the maximum battery size estimated for each vessel (~90%). Differences in our findings for the battery feasibility of the Trondheim-Brekstad route with e.g. the Brødrene AA et al. (2017) study may be due to the optimistic charging power considered here (10 MW), whilst the other

Table 6

Allocated hydrogen and battery energy demand to harbours, that together reflect around 35% of identified vessel energy demand in each case. Note: only the energy needs of identified candidate vessels are included here.

Zero-emission technology	Harbour name	Annual energy demand (GWh)	Annual hydrogen demand (t)	Allocated energy demand (% total of the vessels suitable for replacement)	Location description (inhabitants)
Hydrogen	Østre havn, Stavanger	3.0	182.5	7.9	City (143 691)
	Havneveien, Alta	2.1	124.1	5.4	City (20 789)
	Kleppestø kai, Askøy	1.9	112.1	4.8	Town (23 438)
	Sjøgata, Harstad	1.9	111.6	4.8	Town (24 703)
	Vanvikan, Indre fosen	1.6	96.5	4.2	Town (729)
	Hallvika, Havøysund	1.6	95.6	4.1	Town (976)
	Strandkaien, Bergen	1.5	92.8	4.0	City (259 958)
Battery	Florø havn	1.2	–	11.9	City (9 028)
	Eivindvikvegen 1096, Gulen	1,0	–	9.8	Town (315)
	Mjømna, Gulen	1.0	–	9.3	Island (60)
	Markedsgata, Stokkmarknes	1.0	.	9.2	Town (3 445)

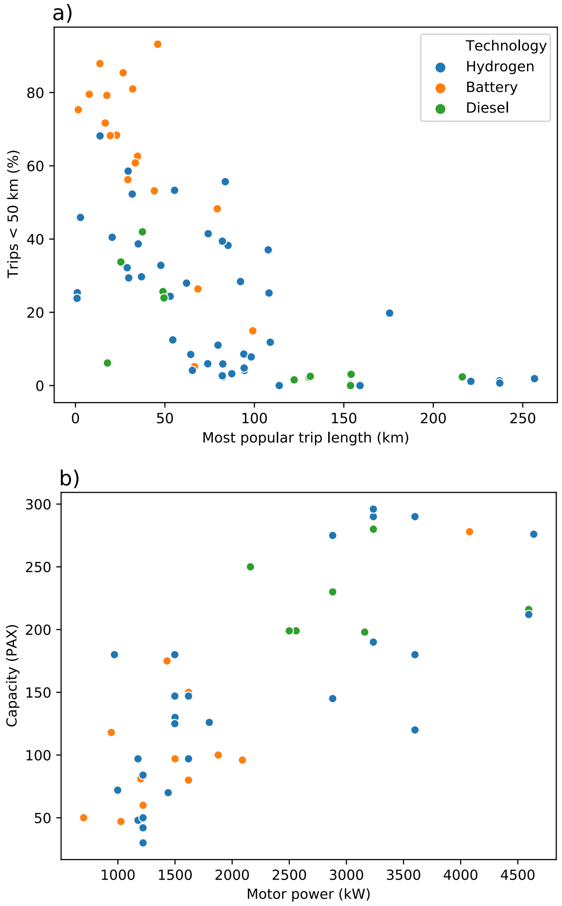

Fig. 9. Correlation of a) movement based on trips with 15 min cut-off and b) vessel characteristics with the identified potential feasibility of zero-emission conversion (based on distance covered statistic).

authors cite that only 1–2 MW shore power is available at these locations (see also section 3.4).

Our study is complementary to other feasibility studies since it is holistic based on overall vessel movements and generalised assumptions. Due to its nature, the feasibility of zero-emission technology used on singular routes thus does not necessarily correlate well with the feasibility of replacing the vessel based on all movements. For example, for the MS Trondheimsfjord I and II that we identify as serving the Trondheim-Vanvikan route (identified as battery feasible), the total annual distance covered by the vessels that can be satisfied by batteries is 8 and 88% respectively. Thus, although the MS Trondheimsfjord II represents a relatively good candidate for overall battery replacement, the MS Trondheimsfjord I does not when all movements are accounted for.

Overall, since the Trøndelag vessels serve a mixture of short and long routes, requirements for one route may be quite different from requirements for another. This again reinforces the perspective that the demands of singular routes alone should not be focused upon when considering zero-emission technology, since by doing so overall vessel requirements are ignored. Instead, wider route and timetable optimisations are required, unless the number of vessels utilised in the fleet is substantially increased to satisfy every route-level requirement.

3.4. Analysis of feasibility assumptions

Feasibility results are dependent on the assumptions made. For example, an increase in the assumed battery storage capacity increases the maximum energy available if there is time/high enough charging powers to fully charge in between trips.

The effects on the mean distance possible to cover with batteries for all vessels, with changes in the assumed battery storage capacity and charging power, are shown in Fig. 10 for two cut-off times. The mean distance covered increases with larger storage capacities and higher charging powers, but with different trends for the two cut-off times. When the time cut-off is set to 5 min, results show it is too short to charge fully; the coverage is rather similar for all storage capacities even at maximum charging power meaning that time is a limiting factor in this case. For time cut-offs of 15 min (Fig. 10 a) this change and increased storage capacities make a difference at all charging powers. Note that since these cut-off times are not individually set to fully charge for each vessel, as in the main results, the distances covered found here are not the same as given in section 3.2.

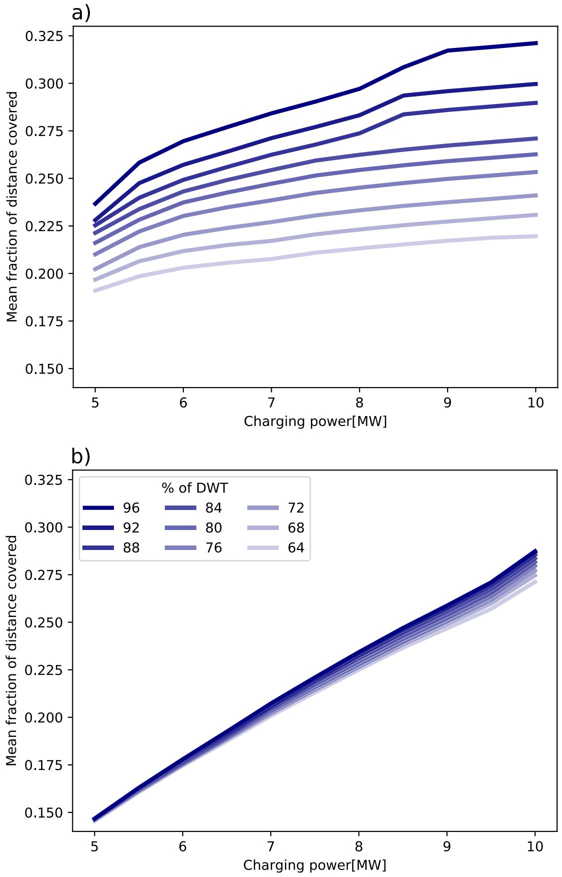

Fig. 10. Fraction of mean distance covered for different settings of the charging power (x-axis) and storage capacity as a fraction of the DWT, from light blue (64% of DWT) to dark blue (96% of DWT). Figure a) is for a cut-off time of 15 min and b) is with a cut-off time of 5 min. The legend is for both a) and b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This analysis further indicates the need for adapting the routes and timetable to the available charging powers and storage capacities. With the short cut-offs, the distance between assumed charging stops becomes shorter, and hence charging opportunities at most harbours served are needed to cover the vessels' energy demand. As the lower charging powers tested here gave very low mean distance covered and almost no vessels above 90%, as also mentioned earlier, a challenge will be to deliver high enough powers at all needed locations along the coast for battery high speed vessels to be feasible, while keeping the current level of timetabled service.

For further exploration of the hydrogen feasibility assumptions, two different time-cut offs were applied of 200 and 100 min. In Fig. 11 the results of distance covered are shown in relation to changing the settings of assumed hydrogen storage capacity and time for refuelling. As expected, the mean distance covered is much larger for hydrogen than for the battery case (see also Fig. 8). The dependence of the two settings show quite similar patterns for the two time cut-offs. Both cut-offs give lower distance covered for lower storage capacities and are rather independent of change in refuelling times per kg hydrogen except at the largest storage capacities and lowest bunkering speeds. What we also note here is that the time cut-off of 100 min gives overall the largest mean of the distance covered. When the 100 min cut-off time was used, between 34 and 46 vessels covered more than 90% their distances. The span decreased to 29–27 vessels when the 200 min cut off was applied.

From this we can conclude that even if daily bunkering can be a feasible strategy for some vessels, more are suited for replacement with the option of bunkering in between trips. Hence, and as with the battery electric options, there is a need to optimise bunkering frequency individually for each vessel and routes. Bunkering speeds in the range we have used here do not seem to be a critical parameter overall. The possible limitations of storage capacities for some vessels might be overcome with some adaptation in the vessel service. In general, bunkering events per vessel will be far fewer compared to needs for charging, and the number of harbours with need of a new on-shore infrastructure will be accordingly lower.

4. Conclusions

We estimate in this study a total energy demand for the 73 high-speed Norwegian passenger vessels analysed of 151 GWh for the year 2018. Based on energy demand estimations coupled with individual vessel movements, and assuming charging or bunkering

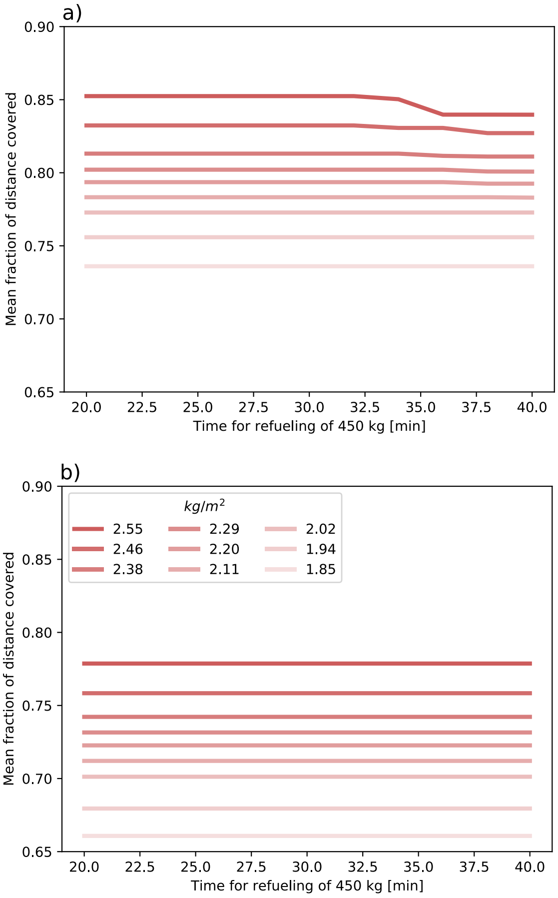

Fig. 11. Fraction of mean distance covered for different settings of the refuelling speeds (x-axis) and storage capacity (from light red 1.85 kg/m^2 to dark red 2.55 kg/m^2), a) is for a cut-off time of 100 min and b) is with a cut-off time of 200 min. The legend is for both a) and b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

occurs between trips in the time available, we isolate here 12 and 51 vessels that are candidates for replacement with battery and hydrogen electric power, respectively, where 90% of their covered distance can be satisfied by each zero-emission propulsion technology. The power of our approach is that we do not limit our feasibility analysis to a route level, reflecting the movements of the vessels over the whole year. Nonetheless, route level results can also be extracted and analysed, which seem to correlate well with other feasibility studies in the literature.

Despite results indicating that a large proportion of the fleet, representing 60% of the total energy demand, can be replaced with zero-emission propulsion technology, we nevertheless identify 22 vessels that do not appear to be good candidates for either battery and compressed hydrogen electric power replacement given their current high energy demands and timetabled requirements.

These results imply that optimising and adapting the vessel services and routes to balance out the limitations of the zero-emission technology is required to reach Norwegian zero-emission public transport targets. This is instead of the current approach that largely attempts to apply zero-emission technology based on the existing fleet demands and service. That structural changes to the transport system are needed is further supported by our findings of energy allocation to harbours, based on the location where each vessel spends the longest duration each day. These results show major hubs for energy demand in large cities, but also islands and more remote places that are potentially not able to supply the charging powers and hydrogen needed, at least not within reasonable costs. Our analysis indicates that very high charging powers in general seem to be essential to be able to hold the scheduled harbour stops and for battery electric propulsion to be feasible, which is a major current challenge.

Estimates given here are made assuming that no changes are made to timetabled activity or to vessel characteristics after replacement and do not take into account local conditions, meaning that our results represent only the first step in a required chain of feasibility studies. We therefore recommend that these results are used as a basis for detailed feasibility studies of the identified candidates. Such in-depth studies could take into account changes to vessel weight, efficiency and more accurate storage capacities and on-board arrangements for new builds, as well as route optimisation studies and cost analysis. In addition, further analysis of the necessary on-shore infrastructure is required, using the results presented here as a guide.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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