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The *E-ferry*: Energy efficient hull design

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Abstract

The *E-ferry* is a fully electric, battery-powered passenger ferry, which will run on green wind mill energy and consequently will have no greenhouse gas (GHG) emission. As a fully emission free vessel, the *E-ferry* is exempt from following IMO' Energy Efficiency Design Index (EEDI). Current battery technology means, however, that the more energy a vessel requires, the more battery capacity needs to be installed, and the more weighty and costly it will be to build. Consequently, fully electric vessels need to be designed in the most energy efficient manner possible. In this paper, we discuss different parameters that can be adjusted to decrease the power consumption of vessels. We conclude that most of these solutions are neither socio-economically or operationally feasible for passenger ferries. We consequently propose one main design dimension that can reduce the energy requirement of battery-powered passenger ferries - hull design – and present the *E-ferry* hull.

Keywords: battery-powered vessels, hull design, energy efficiency index, zero emission maritime transport

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1. The *E-ferry*: a battery-powered zero emission passenger ferry

The *E-ferry* is a full-scale design- construction- and demonstration project of the next generation 100% electrically powered ferry for passengers and vehicles, funded by the EU Horizon 2020 program. The aim of the project is to design and develop, then build and finally demonstrate a fully battery powered passenger ferry that can operate on longer distances than seen so far (Gagatsi et al., 2016). Compared to a conventional ferry of the same size, capacity, and operation, the *E-ferry* prototype is expected to reduce greenhouse gas (GHG) emission with 2.000 ton CO_2 and 41 ton NO_x per year, assuming that the batteries will be charged from sustainable energy-sources, i.e. electricity produced through wind power. In other words, the *E-ferry* prototype will be entirely free of GHG emissions, when under operation.

The *E-ferry* design is scalable in terms of size, capacity, power and speed, but the prototype that is currently under construction is dimensioned according to the operational profile on the route(s) on which it is to be demonstrated: The Søby-Fynshav and Søby-Faaborg routes operating from the island of Ærø in the South Funen Archipelago of the Baltic Sea (see Fig. 1).

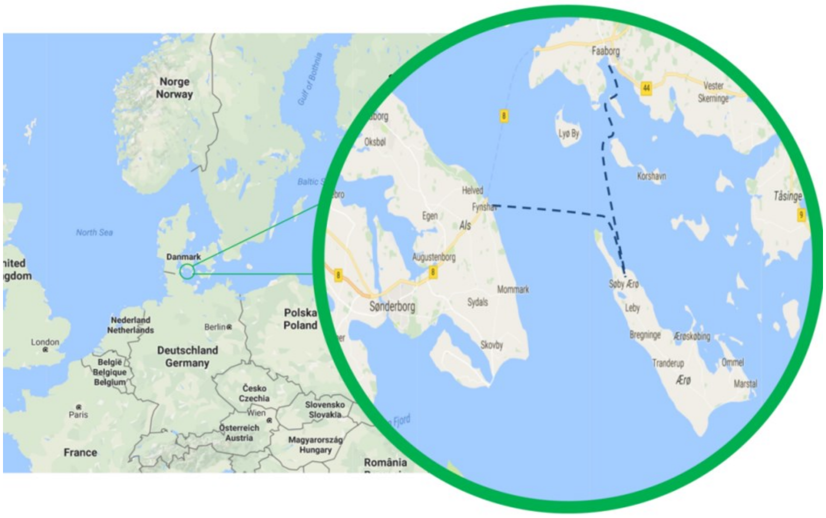

Fig. 1 Operating profile of the *E-ferry* prototype

The physical dimensions of the *E-ferry* prototype have been specified in terms of capacity for transported units, specifically the number of cars (including trucks) and passengers that need to be transported for each trip. The power and propulsion system has been dimensioned according to the time over distance that each trip can last, and finally, the battery capacity has been dimensioned according to the distance to be covered between charges in relation to the power needed for that distance (see Hagbarth Mikkelsen, 2015 for details). See Table 1.

Table 1. *E-ferry* prototype design specifications

	Technical characteristics
Type	Single ended, drive-through Ro-Ro passenger ferry
Class notation	1A1, Car Ferry B, R4, ICE C, EO, Battery (Power)
Transport capacity	31 cars or 4 trucks and 8 cars, 147 passengers in winter, 196 passengers in summer
Dimensions	Length 59.4 m, breadth 12.8-13.4 m
Speed (draught of 2.30 m)	13-15.5 knots
Deadweight	235 ton
Gross tonnage	996 ton
Propulsion	2x750kW main motors, 2x250kW thruster motors
Battery capacity	4.3MWh
Charging capability	4MW
Battery weight	56 ton

To reduce the costs of installing on-shore charging equipment, the *E-ferry* prototype will only be charging in one port, Søby. Consequently, the distance that the *E-ferry* has to cover between charges equal one return trip from Søby to either Fynshav (2x10.7 nautical miles) or Faaborg (2x9.6 nautical miles), meaning that the *E-ferry* will have to be able to cover a distance of up to 22 nautical miles between charges. The *E-ferry* will operate a maximum of 7 return trips per day. This gives the *E-ferry* the energy balance illustrated in Figure 2.

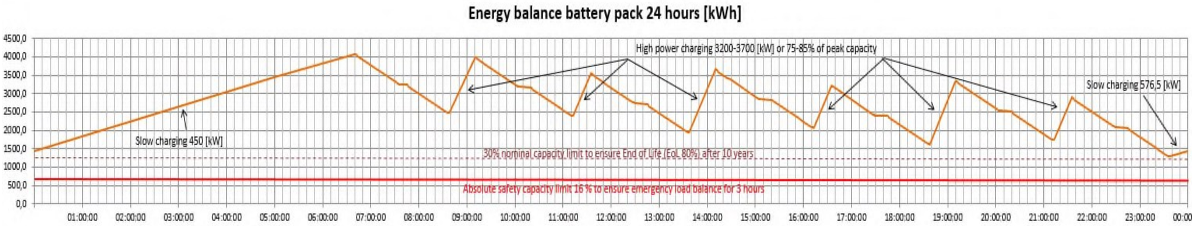

Fig. 2 Energy balance of the *E-ferry*

As the Energy Balance illustrates, the *E-ferry* – as well as any other fully electric battery-driven vessel – is extremely sensitive to energy consumption, as every additional kWh needed for propulsion (or other consumers) will require additional battery capacity. Increasing the battery capacity in turn increases the weight of the batteries and the overall vessel, which in turn increases the energy consumption, and so on and so on. This means that even though the energy used for the *E-ferry* is entirely GHG emission free, the *E-ferry*, as all other new vessels, must be designed in the most energy efficient manner possible. Consequently, though the *E-ferry* is in principle exempt from the Energy Efficiency Index (EEDI) introduced by IMO in 2013, the overall design of the *E-ferry* has been investigated on the basis of the EEDI. In the following, we discuss how the different measures that have been proposed to increase the energy efficiency of vessels may or may not apply to the *E-ferry* concept.

2. The Energy Efficiency Index (EEDI) and greenhouse gas emission in maritime transport and shipping

The need to decrease greenhouse gas (GHG) emissions in maritime transport and shipping has been discussed for at least a decade. Actual energy efficiency regulations entered into force on January 1, 2013, where an amendment to Annex VI of MARPOL (Imo, 2011) introduced both the Energy Efficiency Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). The EEDI serves as a benchmark for the design of all new ships over 400 gross tonnage by providing a reference line for the allowable EEDI value limit for any given deadweight (IMO, 2012a). The SEEMP on the other hand applies to both new and existing ships over 400 gross tonnage, and is a management plan that must be developed for all such ships, detailing the operational measures that can be implemented to reduce GHG emissions (IMO, 2012b).

By being fueled exclusively by green, wind mill generated electricity, the *E-ferry's* EEDI value is effectively zero, just as is the GHG emissions. However, both the EEDI and the SEEMP are based on the basic assumption that a reduction in GHG emissions is best achieved by a reduction in fuel consumption. Many of the measures that according to IMO (Buhaug et al., 2009) can be implemented to obtain a better EEDI thus also result in increased energy efficiency. As noted above, energy efficiency is of extreme importance for battery driven vessels such as the *E-ferry*; this in turn makes the implementation of one or more of the by IMO suggested measures lowering the EEDI value of extreme relevance even for a zero-emission vessel such as the *E-ferry*.

2.1. Emission and energy reduction measures

A number of both empirical and theoretical studies have focused on the relative effectiveness of the measures to reduce GHG emissions. While these studies do not always agree on the actual possible reduction that can be achieved by implementing one or more measures, nor on which of the suggested measures are the most effective, general consensus is that there are some measures with the potential for reducing fuel consumption/increasing energy efficiency. In a recent review of about 150 studies, Bouman et al. (2017) summarize 6 measures:

- Economy of scale
- Power and propulsion
- Speed
- Weather routing and scheduling

- Fuels and alternative energy sources
- Hull design

Most of the measures are directed at tankers and bulk carriers that are significantly bigger and heavier (larger gross tonnage and deadweight) than the standard passenger ferry; moreover the operational profile of tankers and bulk carriers naturally differ dramatically from that of passenger ferries. Consequently, it is not a given that the suggested measures will in fact lead to GHG reduction or increased energy efficiency for passenger ferries such as the *E-ferry*, nor is it the case that these measures can be practically implemented with respect to the specific operational requirements of a passenger ferry (see Banks et al., 2013, for a similar position). In the following, we briefly summarize each of the proposed measures and discuss their application potential for passenger ferries such as the *E-ferry*, i.e. vessels of relative low gross tonnage and deadweight and with operational requirements that among other things include a certain capacity and frequency, inflexible ports and times of arrival and – usually a set schedule as well. We conclude that the implementation of the first five measures are either irrelevant or operationally impractical when it comes to a standard passenger ferry such as the *E-ferry*, independently of whether their implementation would increase the energy efficiency of said type of vessel.

2.2. Economy of scale

Economy of scale refers to the general finding that the energy-efficiency per freight unit typically increases in direct relation to the vessel's size. According to Bouman et al. (2017), for instance, a doubling in cargo capacity will only increase the power consumption by two thirds. Similar calculations have been presented by Notteboom and Verminen (2009), Stott and Wright (2011) and Lindstad and Eskeland (2015). Buhaug et al. (2009: 46) similarly posit that "using large ships tends to reduce energy consumption", but note that the reduction is achieved in the specific shipping leg only, whereas "the total impact on overall door-to-door logistics performance may be negative". Consequently, in the larger picture of world-wide maritime logistics, smaller ships that have access to more ports and are more likely to fill its cargo hold to full capacity may turn out to be more energy efficient in the long run. This latter observation can be applied more or less directly to the operational requirements of a passenger ferry, and certainly for the operational profile of the *E-ferry* proto-type. All passenger ferries need to meet the requirements of their specific operating profile, with size and capacity being pre-defined by both the size of the ports it has to access as well as the number of passengers, cars and other cargo that need to be carried from one port to the other. Thus, a doubling in cargo capacity such as that suggested by Bouman et al. (2017) may reduce the power – or energy – consumption per transported unit, but such reduction make little sense for a passenger ferry, given that there may not be units (i.e. passengers) enough available to make use of the increased capacity unless the frequency of operation is reduced, which in turn could be problematic for other reasons (see section 2.5).

2.3. Power and propulsion

Power and propulsion systems can be adjusted, calibrated or exchanged in various ways to reduce either GHG emissions or energy consumption. To specifically reduce NO_x and SO_x emissions, for instance, technologies such as Selective Catalytic Reduction, Exhaust Gas Recirculation and exhaust scrubbers can be installed on existing vessels running on Heavy Fuel Oil and Marine Diesel Oil. These technologies may, however, have an adverse effect on CO_2 emissions (and operational costs), as they typically decrease the energy efficiency of the propulsion system (Livanos et al., 2014). Another alternative is derating of the main engine so that it can run on a lower shaft speed and lower mean effective cylinder pressure (e.g., Kristensen, 2012). This will decrease the fuel consumption of the engine, but is a somewhat costly solution that in addition typically adds weight. While it is thus possible, but not always economically attractive, to reduce at least No_x and So_x emissions from conventional power and propulsion systems, others have pointed out that the issue should perhaps be tackled somewhat differently. According to Lindstad et al. (2015:95), for instance, the main issue with conventional power and propulsion systems is that they are "generally environmentally inefficient in part by having insufficient flexibility". Focusing on cargo vessels with 17.000 DWT, they consequently propose two alternative propulsion systems that increase flexibility: a multiple-engine configuration and an advanced engine control system. For both alternatives, Heavy Fuel Oil or Marine Diesel Oil (both with reduced sulphur content) can remain the main fuel source, with batteries being used for energy storage and peak load shaving (see also section 2.6). Independently of what technological solutions that have been suggested to reduce the GHG emissions or energy consumption of power and propulsion systems, the introduction of a fully electric, battery powered vessel clearly makes all of these proposals obsolete, as there are no GHG emissions to reduce and as a fully electric propulsion system is in effect the most flexible system that can be obtained, in terms of energy efficiency.

2.4. Speed

Across studies and theoretical calculations, the general consensus seems to be that a reduction in speed is not only a certain measure for reducing energy consumption, but also one of the most efficient means for doing so, with estimates ranging from 1-60% (Bouman et al., 2017; see also Faber et al., 2010; Corbett et al., 2010). The relatively high potential for reduction in energy consumption through decreased speed is, however, based at least partially on the assumption that a vessel's design speed is set at the hydrodynamic boundary speed, which is also the point at which the biggest fuel reductions can be obtained, if the operational speed of the vessel is decreased. Kristensen (2012) calculates that the benefit of decreasing speed in terms of the EEDI is most pronounced for smaller ships (though this still relates to container ships rather than passenger ferries). He also notes, however, that when the speed of a cargo transporting vessel is lowered, "more cargo carrying capacity is needed for the same amount of cargo to be transported **per time unit**" (our emphasis), thus pointing to the same possibility as Buhaug et al. (2009: 46) does for *economy of scale* measures, namely that the benefit (environmental as well as economic) of decreasing speed may be very local only, whereas the overall impact on logistic performance may in fact be negative. This potential problem with reducing speed to obtain less energy consumption certainly applies to passenger ferries, in particular those that serve as the sole connection between islands and the mainland, as it the case for the *E-ferry* prototype: to decrease the speed of a passenger ferry automatically means that travel time for passengers is increased; if this increase is beyond a certain level of tolerance, daily commuting to work, as well as transportation of goods and service to local businesses, will no longer be tenable. This in turn may have serious socio-economic consequences, with people and businesses moving to the mainland instead, which of course in turn would mean that the passenger ferry would have less units (passengers) to transport on a daily basis.

2.5. Weather routing and scheduling

Weather routing and scheduling is another measure for reducing GHG emissions and power consumption that many agree is efficient, as well as economically tenable. In Bouman et al. (2017) terms, weather routing and scheduling consists of "finding the optimum sailing route and speeds, taking into account current, wave and weather conditions, and **deliveries according to the contractual agreement or published schedules**, to minimize resistance and fuel consumption." (410: our emphasis). Passenger ferries of the *E-ferry* type typically operate over relatively short distances, with sailing routes that are relatively strictly defined by port of arrival and departure, as well as by coastal boundaries, potential protected habitats and finally, water depth along the route (see also Papanikolaou et al., 2016). While small adjustments to the sailing route may be possible, this is for passenger ferries often a very limited possibility. Moreover, both an adjustment in speed, as well as a change of sailing route, will in all likelihood impact negatively on the time of travel (see also section 2.4 above); for ferry operators who are bound by contractual agreements and published schedules, such adjustments may eventually prove very costly, as both their contractors and their passengers may claim compensation.

2.6. Fuels and alternative energy sources

In Bouman et al.'s (2017) overview, the reductions that can be achieved through the use of alternative fuels and energy sources score rather differently, from 0.2% to 84%, depending firstly on the type of alternative fuel or energy source, and secondly on the scope of their use. A range of studies thus report a relatively high potential effect on energy efficiency and/or emission reduction (of CO_2) by switching to biofuels or LNG (e.g. Lindstad et al., 2015, Livanos et al., 2014). Somewhat surprisingly, it seems that the use of alternative energy sources, such as wind power, solar power, fuel cells or power from shore (i.e. batteries) score lower on the effect on energy efficiency and emission reduction, but this is likely due to the fact that studies so far have mainly considered the use of alternative energy sources as a complementary or hybrid solution, where the main power resource for propulsion is still diesel or some other fossil fuel. As noted above, the *E-ferry* concept – and the *E-ferry* prototype – is a fully electric solution, with green and emission free electricity charged from shore and stored in batteries onboard the vessel being not just the main source of power, but the only source. Consequently, the reduction of emissions is 100%.

2.7. Summary on energy efficient and emission reducing measures in accordance with EEDI

As have been discussed above, the suggested measures to increase energy efficiency and/or reduce GHG emissions are many, they can be applied at different level (e.g. operation, construction, refitting, design etc.), and they are more or less costly, in economic terms. Though the effect of individual measures is not always agreed upon and though some argue that certain measures have negative effects in other areas (cost, logistics, other types of emissions), there does appear to be a relatively strong degree of consensus among scholars that all of the described measures do have some positive effect, and that there is the potential to reduce emissions by 50-60% per freight unit, by implementing some or all of the measures discussed (Bouman et al., 2017). Though the *E-ferry* concept is based on a no-emission solution where the vessel is powered by wind generated electricity from shore, which is stored in batteries onboard, we have so far considered whether any of the measures that have been proposed in relation to the EEDI would be relevant for the *E-ferry* and could feasibly be implemented, to increase the *E-ferry*'s energy efficiency. Based on the above, we have so far concluded that certain measures apply at best peripherally, at worst detrimentally, to a fully electric passenger ferry of the *E-ferry* type and size. To adjust scale, speed, routing and scheduling is, for instance, not amenable to the concept of passenger transport over relatively short distances, where frequency and timing is of the essence. Other measures, we conclude, are in fact implemented in the *E-ferry* by default; this relates in particular to the power and propulsion system and the use of alternative energy resources. What remains to be discussed is one final measure that has been proven to reduce the energy consumption of a vessel, namely hull design. In the following, we will consider this measure in more detail and present how the hull of the *E-ferry* has been designed to increase energy efficiency.

3. Hull design as a measure for increased energy efficiency

Hull design typically covers aspects such as overall hull dimensions, hull shape and weight. According to Bouman et al (2017) hull design that improves the hydrodynamic performance and minimizes the resistance of a ship can contribute significantly to reducing energy consumptions. Kristensen and Lützen (2012) illustrate how the general trend towards designing tankers and bulk carriers with increasing block coefficient and decreasing length displacement ratio over the last 30-40 years has led to an increase in needed propulsion power for this type of vessel, with an increase in fuel consumption and GHG emission to follow. Using computer modelling to alter the dimensions of a 100.000 dead weight ton (dwt) Aframax tanker, they argue that a combined change of length and draught of only 2% can decrease the propulsion power by 15%. Similar findings are suggested by e.g. Lindstad and Eskeland (2015) and Stott and Wright (2011).

In terms of deadweight and its relation to a vessel's fuel consumption, results are less clear. According to Kristensen and Lützen (2012), for instance, the deadweight of Panamax tankers has increased over the last 40 years (from app. 55.000 tons to app. 75.000 tons). Given that the EEDI is a decreasing function of the deadweight, a reduction of the EEDI would thus be expected for Panamax tankers, but according to Kristensen and Lützen (2012) the exact opposite has in fact occurred and the EEDI for Panamax tankers are increasing along with the increase in deadweight. This suggests that weight reductions are less relevant for gaining reductions in power consumption than are other measures, a position which is also taken by Bouman et al. (2017), who note that "Additional measures, such as **light-weighting**, hull coating and lubrication can **contribute** to improving the performance of hulls further, **but their potential as a single measure is limited**." (pp. 413, our emphasis).

Overall, the consensus on hull design in relation to energy efficiency is to build more slender vessels with lower block coefficient. As with the other measures to reduce GHG emission and/or increase energy efficiency, these rather general recommendations are based on larger cargo-carrying vessels, rather than smaller passenger carrying vessels. However, as hull dimension and shape has a direct relation to hydrodynamics and resistance, and hence to the required power needed for a vessel to operate at a given speed, it is highly likely that the hull design of a passenger ferry such as the *E-ferry* can have a significant impact on said vessel's consumption of propulsion power and hence that a high level of energy efficiency can be reached by paying particular attention to this aspect of the overall vessel design. Given that the *E-ferry* prototype – along with any future fully electric battery-powered vessels – is dependent on being energy efficient to reduce the cost and weight of additional batteries, the hull design has consequently received much attention in the design phase of the *E-ferry* project. In the following we present the final design of the *E-ferry* hull, and based on the hydrodynamic data of the *E-ferry* hull, discuss the degree to which it has been possible to design a more energy efficient hull, when compared to other existing vessels of the same size, capacity and operational profile and when taking into consideration other design requirements, with respect to for instance stability and trim.

3.1. The E-ferry hull design

While hull design can be optimized with respect to energy efficiency, there are of course number of other issues that have to be taken into account with respect to the hull design of a passenger ferry. Firstly, the ferry operator may have specific requirements, e.g. in terms of capacity (number of passengers, cars etc. transported per trip), frequency, speed and manning. Secondly, port and route conditions may introduce limitations, e.g. with respect to breadth, length and draught. Finally, other requirements from approving maritime authorities need also to be met, for instance with respect to stability and buoyancy. Table 2 provides an overview of the main requirements, which the *E-ferry* prototype has been designed to meet (see Table 1 above for other design specifications).

Table 2. *E-ferry* main requirements

	Technical characteristics
Capacity	Room for 31 cars on car deck, seats for 147 passengers in covered areas.
Service speed	>13 knots to maintain required frequency
Breadth	13.4 meters to best fit existing harbors
Draught	>2.5 meters at 230 tons deadweight
Passenger area and evacuation	On car deck level to minimize manning as much as possible

To meet the requirements of maximum breadth, capacity and passenger area on car deck level, the *E-ferry* prototype has been calculated to need a length of about 59-60 meters, which will provide room for the required number of cars (car deck breadth allows for three rows of cars or two rows of trucks) as well as a unit for passenger accommodation along the car deck. This length has also been calculated to accommodate the required service speed of 13 knots without causing interference between the bow and stern wave. To determine the freeboard and optimize it as far as possible with respect to reserve buoyancy and stability, the height of quays, access conditions to car deck, tidal conditions and draught and trim during berthing and loading of cars has been considered, with the result being a hull depth of 3.70 meters. Based on these main dimensional requirements, the hull has been shaped to optimize energy efficiency (reduced resistance and wake) alongside issues such as maneuverability, sea keeping and stability. Fig. 3 provides an illustration of the overall shape of the hull, as seen through a line drawing, Fig. 4 provides a similar illustration through plots created with NAPA Oy software.

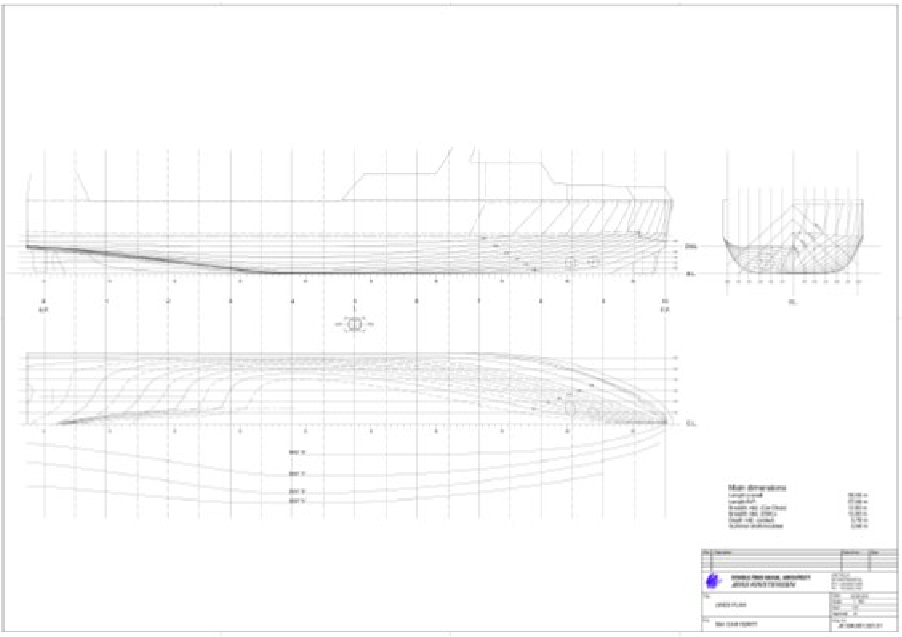

Fig. 3 Line drawings for the *E-ferry* hull

As can be seen from Fig. 3 and Fig.4, the *E-ferry* hull has been designed with a fore body with a relatively V-shaped sloping bow, this in order to make space for a bow rudder. The aft body is designed with U-shaped frames, as a barge form, which maximizes the car deck area in the aft body, but also provides a good wake, with positive influence on the propeller performance and minimization of vibration (due to good clearing, i.e. distance between propeller and hull).

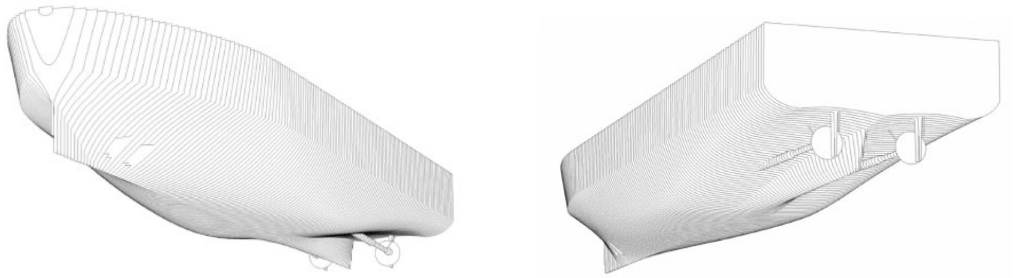

Fig. 4 (a) Plot of the *E-ferry* hull from stem; (b) Plot of the *E-ferry* hull from stern

Whereas the overall hull is designed with slenderness in mind, the midship section has been designed to be as full as possible, this to decrease the prismatic coefficient (hull fullness/midship section fullness) and hence the wave resistance, in accordance with the Guldhammer & Harvald method. Fig. 5 provides a plot of the wave system at 11, 13 and 15 knots, Fig. 6 provides an illustrative comparison between the *E-ferry* and current comparable existing ferries.

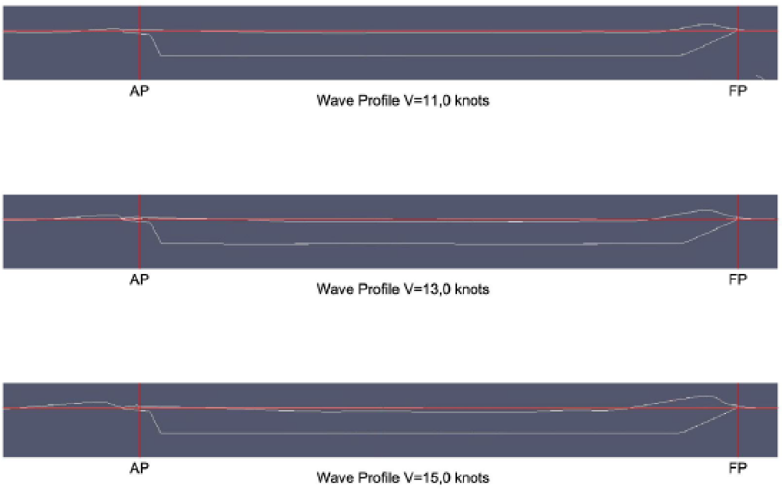

Fig. 5 Plot of the *E-ferry* wave system at 11, 13 and 15 knots

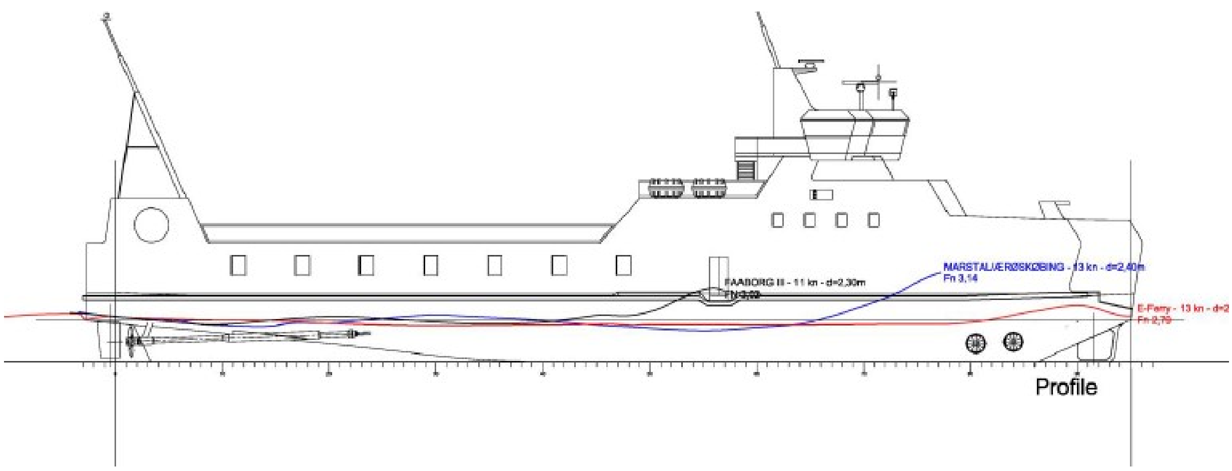

Fig. 6 (a) Plot of the *E-ferry* wave system (at 13 knots) compared with existing, comparable passenger ferries.

To determine the hull resistance of the *E-ferry* prototype, several different methods of calculations, including CFD has been used and compared. As illustrated in Fig. 6, the calculation methods do not differ dramatically with respect to the overall result, but both the Guldhammer and Harvald and the Holtrop and Mennen methods deliver a more conservative estimation of energy efficiency than does the CFD calculations.

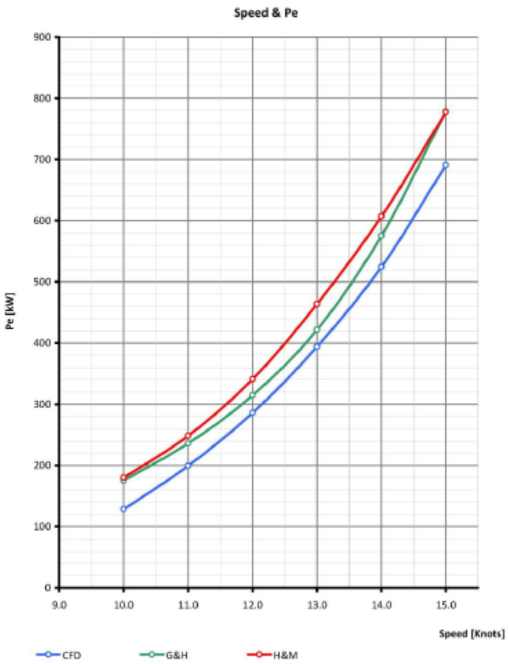

Fig. 6 Hull resistance as effective power from CFD calculations, Guldhammer and Harvald method and Holtrop and Mennen method

It is the more conservative calculations, i.e. Guldhammer and Harvald that has been used for determining the *E-ferry* energy balance and the overall hull design. Independent calculations of the overall hydrodynamics of the *E-ferry* have been done by Kongsberg, in connection with the development of a simulation program for the *E-ferry*, and these calculations also suggest that the calculations of *E-ferry* hull resistance are conservative. The basic hydrodynamic data generated in this way are provided in Table 3.

Table 3. *E-ferry* hydrodynamics, from Kongsberg simulator model

C_w – Water plane coeffecient	0.768
C_m – Midship section coefficient	0.869
C_b – Block coefficient	0.491
C_p – Prismatic coefficient	0.565

4. Concluding discussion

Based on recommendations for how to reduce power consumption and/or GHG emissions in relation to the EEDI, the overall design of the *E-ferry* has been weighted against these recommendations. Though most of the recommendations are provided for larger cargo-carrying vessels, each of the main recommendations has been considered. We have concluded that some recommendations are simply too impractical to follow for passenger carrying vessels that need to meet operational requirements for speed, frequency and capacity, and that are furthermore limited by considerations regarding route and scheduling flexibility. For other recommendations, the *E-ferry* goes well beyond what is proposed, i.e. in terms of power and propulsion systems, as well as in terms of using alternative energy resources. While the *E-ferry*, due to in particular the two latter aspects goes well beyond any EEDI requirements, by being a zero-GHG-emission vessel, measures to reduce energy consumption are nevertheless relevant. Consequently, the *E-ferry* design team has focused especially on designing a hull that is optimized in terms of hydrodynamic and resistance. In doing so, matters such as operational specifications, intact stability and other relevant issues have of course to be taken into consideration. Nevertheless, we believe that the final hull design of the *E-ferry* is optimized as far as is possible, in terms of hydrodynamics, resistance and power consumption. This is attested by the theoretical calculations provided in section 3. However, a final evaluation of the energy efficiency of the *E-ferry* can only be provided when the *E-ferry* is put into operation, at which point a detailed empirical study will be conducted to investigate these and other aspects of the *E-ferry*'s performance (see Huppunen et al., 2017).

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