Evaluating the Economic Performance of a Pure Electric and Diesel Vessel: The Case of E-ferry in Denmark

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Europe is an extremely ferry-intensive area, with two main markets – the Northern Europe and the Baltic, and the Mediterranean; while EU ferries account for 35 % of the world fleet. This research presents the E-ferry, the first pure electric ferry for medium range routes and likely the largest battery pack ever installed in an electric vessel, and evaluates its economic performance compared to an electric-diesel and a diesel vessel. Three E-ferry schemes are used in the evaluation: E-ferry prototype, E-ferry prototype excluding the development costs, and Series 3 E-ferry, for which we assume an increased production level. The evaluation focuses on the construction and operation costs of the vessels by utilizing real-world data that were collected during the evaluation period of the E-ferry, and complemented with data provided by the ferry operator. The evaluation shows that while the E-ferry construction cost is higher compared to the other two technologies, it contributes significantly to energy demand reduction. The E-ferry achieves cost parity with the diesel-based engine vessels between 5.2 and 3.6 years when considering different E-ferry and energy schemes, showing the potential to promote sustainable ferry operations in short and medium range ferry connections.

KEY WORDS
~ Pure electric ferry
~ Economic assessment
~ Diesel
~ Hybrid
~ Lifecycle cost

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1. INTRODUCTION

Maritime transport emits around 940 million tonnes of carbon dioxide (CO2) annually and is responsible for about 2.5 % of global greenhouse gas (GHG) emissions, while shipping emissions accounted for around 13 % of the overall EU GHG emissions from the transport sector in 2015 (IMO 2015). Maritime shipping uses about 11 % of the transportation sector's petroleum (i.e., 5 million barrels per day), resulting in 1 Gt CO2 emissions annually (IEA 2013). Moreover, maritime air pollutants affect the inhabitants of coastal and harbor areas; the European maritime sulphur dioxide (SO2) and nitrogen oxide (NOx) emissions have been forecasted to surpass corresponding pollutants by land-based activities by 2030 (EC 2005). Moreover, maritime shipping's sheer volume and rapid growth makes it a major consumer of energy and source of carbon and air-polluting emissions.

Compared to the rest of the world, Europe is an extremely ferry intensive area with two main markets: The Northern Europe/the Baltic and the Mediterranean (Wergeland 2012). The domestic market in Greece is the largest single market for ferries carrying more than 40 million passengers every year. Europe has around 900 ferries for both cargo/cars and passengers, which account for 35 % of the world fleet. Considering passenger-only ferries, the total number is around 13,500 units and the majority of them are older than 20 years old (Papanikolaou and Eliopoulou 2001); whereas the majority of the fleet is older than 30 years old in the inland waterways sector. Inland waterways are often used as an alternative to road and rail transportation, and older diesel engine ferries that operate on these routes impact the local environment.

Existing state-of-the-art solutions are based on retrofit, integrating hybrid and on 100 % electric drive train systems suffering from limitation in range, and are only being built and applied for very short ferry connections. Other ferry technologies, currently available in EU market include liquefied natural gas (LNG), liquefied petroleum gas, methanol/ethanol, synthetic fuels (Fischer-Tropsch), biodiesel, biogas, hydrogen and nuclear (Gagatsi et al. 2016), while the main European ferry operators that introduced new technology ferries to their fleets are located in Norway, Germany and Denmark.

Following a business-as usual scenario, the maritime emissions could increase between 50 % and 250 % by 2050, undermining the objectives of the Paris Agreement to limit global warming (IMO 2015). The European Commission formed a strategy towards reducing GHG emissions from the shipping industry in 2013 (EU 2013). The strategy relied on three pillars: a) Monitoring, reporting and verification of CO2 emissions from large ships using EU ports, b) Greenhouse gas reduction targets for the maritime transport sector, and c) Further measures, including market-based measures, in the medium to long term.

Improved technologies and alternative fuels provide significant reductions in GHG emissions and fuel consumption, and minimize the maritime transportation impact. Electric propulsion for short sea ferries will introduce a shift of paradigm for the operational setup in ferry transportation on short and medium range distances (Mikkelsen 2014). This paradigm change will impact ferry operations in various ways. Ferries have a long-life span, often more than 30 years. Replacing fossil fuels and conventional diesel generators with battery electric drive-trains may increase the total energy efficiency, as electric motors have a higher energy-efficiency ratio. On the other hand, the payback time will be longer as the electric ferries' upfront capital cost is higher compared to diesel engines.

A survey conducted to 23 shipowners regarding the main barriers for developing green solutions are the cost of installation/purchase, the cost of operation, the technical maturity/reliability/experience of the new solutions, the lack of competitive (market, financial) incentives, crew and ship safety, the complexity of operations, and the required crew to operate/maintain them (DNV GL 2014).

Previous studies attempted to address these barriers and used simulations to explore the size of the battery pack an electric ferry would require compared to a diesel ferry based on specific routes and ferry characteristics (Palconit and Abundo 2019), and to define the system configuration of a ferry in term of engine power, energy storage and photovoltaic system sizes and percentage of hybrid or pure electric usage (Bianucci et al. 2015).

The E-ferry concept that is presented in this paper aims at supporting and promoting energy efficient, zero GHG emission and air pollution free waterborne transportation for island communities, coastal zones and inland waterways. The E-ferry is a battery electric ferry for medium range connections and likely the largest battery pack ever installed in a vessel with a record-breaking charging power of up to 4 MW allowing for short port stays.

This paper aims to present and explore the economic performance of a pure electric ferry. To achieve its goal, it presents real-world data that were collected during the evaluation period of the E-ferry and uses them in a detailed economic assessment. More specifically, the data are extracted from on-ferry measurements and the operator's database; the economic evaluation is performed by comparing the E-ferry with two diesel-based engine ferries. The economic evaluation includes detailed construction and operation costs, and uses the final outcomes to estimate the cost parity period between the electric and diesel ferries under different schemes. Three E-ferry schemes are used in the evaluation: E-ferry prototype including the development costs, E-ferry prototype excluding the development costs, and Series 3 E-ferry, for which we assume an increased production level. The environmental impact (i.e., carbon dioxide and air emissions) is not included in the present evaluation.

2. BACKGROUND

E-ferry is the outcome of a research project and addresses the urgent need for reducing the European CO2 emissions and air pollution from waterborne transportation by demonstrating the feasibility of a 100 % electrically powered, emission free, medium sized ferry for passengers and cars, trucks and cargo relevant to island communities, coastal zones and inland waterways. The E-ferry prototype is a small/medium sized single-ended Ro-Pax ferry that was designed, constructed and approved by relevant authorities during the project period (i.e., June 2015 to June 2019).

Following the completion and final approvals, it was delivered to the operator (Aeroe-ferries), who put the E-ferry into ordinary operation on the route from Søby-Fynshav in the Southern part of Denmark, on August 15, 2019. By May 2020, the E-ferry prototype has been sailing as an ordinary car and passenger ferry, including a trial period, of 10 months and a total of approximately 1,000 return trips. The E-ferry prototype operates in the Southern Danish area of the Baltic Sea, on the route Søby-Fynshav. The evaluation of the E-ferry focuses on the route Søby-Fynshav (Figure 1 – red dotted route), which is around 22 nautical miles long (return trip).

On-shore facilities for the E-ferry prototype have been prepared in harbors between which the E-ferry operates, i.e., Søby and Fynshav. Each of the harbors has been equipped with an automated mooring system, for faster docking and less crew work. Charging is only possible in Søby harbor, for this reason the docking duration is typically longer in Søby than in Fynshav. The E-ferry prototype charging system is a semi-automated plug-connection, placed on an on-shore ramp that applies to the fore end of the ferry. Main ferry specifications are listed in Table 1.

Figure 1.
E-ferry operation area.

3. EVALUATION METHODOLOGY

The economic evaluation intends to report the construction and operating costs of the E-ferry and to compare them to costs of diesel engine vessels, operating on the same or similar routes. The comparable vessels have been selected and adjusted to fit to the same – or similar - operational patterns of the E-ferry, (i.e., with respect to capacity, safety, speed and frequency of operation). The economic analysis is performed for year 2020.

3.1. Comparable Vessels

The E-ferry is compared to two alternative vessels that are able to operate on the same route and deliver approximately the same service and transportation performance. The two diesel vessels are selected from an operator's perspective (i.e., the operator requires a vessel of a particular size, speed and capacity for a particular route). The two alternatives are: a) A customized diesel-electric vessel, and b) An existing diesel engine vessel.

Other considered options, not included in the analysis, are an LNG-powered vessel, a hydrogen/fuel cell vessel, and a hybrid battery-diesel vessel. For the economic evaluation, the LNG-ferry has been excluded because the environmental benefits are significantly smaller, the hydrogen/fuel cell vessel is a new and unproven technology; and the hybrid battery-diesel solution because the variation in such technology with regard to the relative size of diesel versus electricity consumption is massive.

3.1.1. Diesel-electric Vessel

Based on the main specifications of the E-ferry, the closest candidate vessel is the LMG-50 vessel (Table 1). The main differences between the LMG-50 and the E-ferry, is that the overall dimensions of the LMG-50 are bigger than the E-ferry, and that the motors of the LMG-50 are smaller compared to the E-ferry (2x440 kW versus 2x700 kW). Thus, the LMG-50 has a lower maximum speed and service. To get closer to the E-ferry specifications, the LMG-50 has been further customized, theoretically, into a version we call LMG-50.1 (Table 1). The LMG-50.1 has an equivalent size and passenger capacity to the E-ferry, a similar towing resistance and propulsion speed, class notations (where possible/relevant) and so on. The hull and overall dimensions have been scaled down, and it has been equipped with a strengthened bow visor and deck to make it more suitable for operating on the E-ferry route. To match the operational speed, the LMG-50.1 diesel-electric propulsion system has been upsized. This entails an increase to the propeller/electric engine power from 2x440 kW to 2x700 kW and an addition of a set of two electric thrusters (250 kW each). Table 1 lists the main specifications of the LMG-50.1.

3.1.2. Diesel Vessel

The M/F Marstal (Table 1) was built in 1998-1999 and currently operates on the route from Ærøskøbing to Svendborg. The rationale behind this choice is that small operators when replacing part of their tonnage, they either use a vessel from their fleet or seek in the market for used ferries.

Table 1.
Vessel specifications for the E-ferry, the LMG-50.1 and the M/F Marstal.

		Principal Dimensions		
	E-ferry	LMG-50	LMG-50.1	M/F Marstal
Length, oa	59.4 m.	64,5 m.	59.4 m.	49.9 m.
Length, bp	57.0 m.	60,5 m.	57.0 m.	-
Breadth, moulded	12.8 m.	12,2 m.	12.8 m.	13.1 m.
Depth, moulded	3.70 m.	5 m.	3.70 m.	3.7 m.
Gross tonnage	996 t.	1081 t.	996 t.	1617 t.
Design, draught	2.5 m.	3,3 m.	2.5 m.	-
Service speed	13.5 kn.	11 kn.	13.5 kn.	11.0 kn.
Max speed	14.2 kn.	12 kn.	14.2 kn.	12.0 kn.
		Capacity and Crew		
Number of cars	31	50	31	42
Number of trucks/ trailers	5	5	5	-
Number of passengers	147/196	245	147/196	250/395
Number of crew	3/4	4/5	4/5	5/6
		Power and Propulsion		
Main motors	2x700 kW	2x440 kW	2x700 kW	2x1020 kW
Thruster engines	2x250 kW	-	2x250 kW	-
Nominal battery capacity	4.3 MWh	-	-	-
Charging effect	4 MW	-	-	-
Diesel generator	-		2x1215 kW	-

3.2. Construction Costs

3.2.1. E-ferry

In order to calculate the overall construction cost of the E-ferry, the following cost items have been considered:

- Ferry design and drawings (475,000€), hull construction (2,642,000€) and outfitting costs (7,162,000€), batteries, battery racks and battery control units (4,284,000€), automation, electrical systems and propulsion (2,100,000€);
- Charging (771,000€) and electrical infrastructure on-shore (298,000€);
- One-time connection fee (1,383,000€) referring to a one-time charge for connecting the on-shore electrical infrastructure to the electricity supplier, and is unlikely to occur again;
- Auto mooring (1,147,000€).

Table 2.
E-ferry Construction costs per category in million euros.

	Cost category	Included costs	Prototype	Prototype(-3.5 %)*	E-ferry series 3**
a	E-ferry vessel	Design, hull, outfitting, battery system, propulsion, electric system, automation, approvals	16.66	16.08	13.25
b	On-shore charging system	Charger, cables, inverters, housing, filters, cooling, VAT	1.07	1.03	0.96
c	One-time connection fee	Fee-electricity supplier (10 kV supply and transformers), VAT	1.38	1.38	1.38
d	Auto mooring	2 systems, including installation and VAT	1.15	1.15	1.15
	Total costs incl. auto mooring for two harbors		20.26	19.64	16.74

Note:
** Prototype excl. development cost (3.5 %)*
*** Economies of scale - Build a third E-ferry (incl. charging station)*

The E-ferry construction costs are merged into 4 categories (Table 2): a) the vessel itself, b) electric charging infrastructure, c) auto mooring, and d) one-time connection fee. The reason for forming these categories is, that while the costs for (a) and (b) are specific for an electric vessel, the connection cost (c) is optional and/or could be applied to other vessel types and depends on the number of harbors the vessel docks at. The auto mooring cost (d) depends on the national regulations and may vary significantly. Moreover, costs (a) and (b) include one-time development costs (estimated at 3.5 %), whereas costs (c) and (d) do not. As the auto mooring is in principle optional for the operator (without auto mooring, manning requirements are likely to increase, and operation costs will too) the cost for two auto mooring systems has been added separately.

The construction costs of the E-ferry are adjusted by considering a development cost of 3.5 % and economies of scale. Building a third E-ferry (series 3) results in a 5-10 % cost reduction due to economies of scale (Table 2) (Heinemann et al. 2020). This estimate does not take into account any reduction in the battery cost. The E-ferry batteries are priced in 2015, when the cost was at 1000 €/kWh, whereas batteries cost roughly 500 €/kWh in 2020.

3.2.2. Diesel-electric Vessel

The total cost of constructing the LMG-50.1 is estimated to be 13 million € (2020). The cost includes design, drawings, hull production, outfitting, propulsion and systems approvals. Similarly, to the E-ferry, the LMG-50.1 has been equipped with auto mooring in two harbors to ensure lower manning, at an additional cost of 1.2 million euros (i.e., for two units, one in each harbor of the current route). The LMG-50.1 does not require on-shore electrical infrastructure for charging, nor a charger; thus, the one-time connection fee to the electricity supplier does not apply.

3.2.3. Diesel Vessel

The acquisition cost of the M/F Marstal at the age of 20 years is unknown, so for determining the construction/acquisition cost, the original building cost for the vessel has been updated into today's prices. In 1999, the M/F Marstal was constructed/acquired by the operator for approximately 9.1 million euros (on-shore facilities excluded) (i.e., 12.9 million euros in 2020). Unlike the LMG-50, which is a new build, the specifications of the M/F Marstal cannot be changed, thus operational changes are considered. The M/F Marstal would not be able to obtain the required speed of 12-13 knots that allows to cross shores in 55-60 minutes. Hence a crossing time closer to 70 minutes is accepted for the M/F Marstal. It would be unlikely or very costly to equip the M/F Marstal with auto mooring systems; thus, manning is not reduced.

3.3. Operation Costs

3.3.1. E-ferry Crew Costs

During ordinary operation, the E-ferry performs five return trips per day. It is manned with a safety crew of three members, consisting of a master, a chief officer and a third safety crew (catering person). For the calculation of crew costs, expenses are calculated based on 14 hours shifts per day, with a total average of 420 operating hours per month. The E-ferry requires between 3.10 and 3.24 crew shifts per month to cover 420 operating hours. To operate the vessel with passengers, the operator allocated a full-time supporting engineer (155 hours per month) and a general maintenance supporter for 12 hours a week, or 48 hours a month.

3.3.2. Diesel-electric Vessel Crew Costs

Existing practices for diesel and diesel-electric suggests that the LMG-50.1 (with auto mooring) requires to have a safe manning crew of four members, consisting of a master, a chief officer, a chief engineer and a safety crew/catering (The Danish Maritime Authority 2020). Moreover, crew time could be reduced from 14 to 13 hours shifts per day, compared to the E-ferry, as the LMG-50.1 reduces the harbor time in Søby (charging is required for the E-ferry). Thus, the LMG-50.1 covers five round-trips in one hour less than the E-ferry, which results to a reduction in crew working hours. For the LMG-50.1, the number of total operation hours per month is estimated to be 390 hours, which are covered by 2.88-3.00 crew shifts per month.

3.3.3. M/F Marstal Crew Costs

The M/F Marstal requires a safety and manning crew of five members for up to 145 passengers, or a crew of six members for more than 145 passengers. As it is unlikely the ferry demand to be more than 145 passengers, five staff members are used for the evaluation. The crew consists of a master, a chief officer, a chief engineer, an able seaman and a safety/catering member. Similarly, to the LMG-50.1, 13 hours of operation are used. With a chief engineer and an able seaman onboard at all times, it is assumed that additional supporting crew is not required.

Table 3 lists the crew expenses (rounded to the nearest thousand) for operating the ferries monthly and annually, based on the same salary averages. Wages for each crew category are based on average salaries and include pension and other employee expenses paid by the employer in small Danish ferry companies (The Danish Maritime Authority 2020). Supporting land crew costs are not included as these are not specific to any of the assessed ferries.

Table 3.
Crew costs for operating the E-ferry, the LMG-50.1 and the M/F Marstal.

Crew category	Average salary & expenses €	Crew shifts per month	Monthly cost €	Annual cost €	Annual cost* €
E-ferry					
Master	9,000	3.24	30,000	364,000	374,000
Chief officer	8,000	3.17	26,000	309,000	318,000
Safety	5,000	3.10	15,000	186,000	192,000
Total cost			71,000	858,000	884,000
LMG-50.1					
Master	9,000	3.00	28,000	337,000	348,000
Chief officer	8,000	2.94	24,000	286,000	295,000
Safety crew/ catering	5,000	2.88	14,000	173,000	178,000
Chief engineer	8,000	2.94	24,000	286,000	295,000
Able seaman / maintenance	5,000	0.18	1,000	12,000	12,000
Total crew cost			91,000	1,094,000	1,129,000
M/F Marstal					
Master	9,000	3.00	28,000	337,000	348,000
Chief officer	8,000	2.94	24,000	286,000	295,000
Chief engineer	8,000	2.94	24,000	286,000	29,000
Safety crew/ catering	5,000	2.88	14,000	173,000	178,000
Able seaman / maintenance	5,000	2.88	16,000	187,000	193,000
Total cost			106,000	1,269,000	1,310,000

** Including a pay roll fee. Pay roll fee is a form of Danish tax paid in lieu of VAT; the VAT and the pay roll fee vary for operators. The pay roll fee has been estimated at 6.37 %, of which 50 % is paid in lieu of VAT.*

3.4. Energy Costs

3.4.1. E-ferry

Electricity cost for the E-ferry is estimated based on the same scenario (i.e., five daily trips). The average consumption of the E-ferry for a return trip is 1,600 kWh, this includes the energy used for the hotel load when sailing and at berth in Fynshav. The energy efficiency factor from shore to batteries is 0.92, (i.e., output of 1,600 kWh, requires a 1,739-kWh supply from the grid). When the vessel is connected to the charger in Søby, the hotel consumption occurs during the charging and idling hours at night. The hotel load has been measured to be 55 kW, and it is supplied for 12.5 hours per day at an efficiency rate of 0.92, requiring a total consumption from the E-ferry system of 747.3 kWh per day. The total energy consumption for the E-ferry is estimated to be 9,443 kWh per day and 3,339,480 kWh per year (i.e., 360 working days).

3.4.2. Diesel-electric Vessel

The fuel source, for the LMG-50.1 when it operates (including the hotel load), is Low Sulfur Marine Gas Oil (LSMGO<0.1 %); whereas the fuel source during idling at night (for the hotel load) is electricity.

As the LMG-50.1 is identical to the E-ferry in terms of hull construction and weight, it is assumed that the required propulsion power is the same. The hotel load for the LMG-50.1 is estimated to be doubled (i.e., 110 kW) compared to the E-ferry, due to the presence of auxiliary and high consuming systems, such as lubrications pumps, fuel pumps and cooling. Moreover, the hotel load is supplied from the diesel-electric system, for all harbors. The hotel load when the ferry idles at night is powered from the on-shore power grid. The idling hours for the LMG-50.1 are higher, because it operates the same five trips faster than the E-ferry, due to the lack of charging in the Søby harbor. Finally, the estimated efficiency factor for a diesel generator to the transformer is 0.94.

To calculate the costs for the energy supplied by marine fuel, we consider efficiency issues for diesel engines. In addition to the losses already included, the amount of fuel needed to produce a kWh on a diesel engine is highly dependent on the load at which the engine runs. Four stroke diesel engines typically are used as generators. The LMG-50.1's engine, the Wärtsilä 16V14, normally performs best at around 80 % of engine load, and the Specific Fuel Oil Consumption (SFOC), or fuel efficiency, measured in grams per kWh, is worse when the engine loads are either higher or lower than 80 %. The SFOC of the Wartsila 16V14 Genset at 80-85 % engine load is specified by the manufacturer to be 205.0 g/kWh.

Table 4.
Energy consumption per day for the E-ferry and the LMG-50.1 (5 Return Trips).

Category of consumption	E-ferry	E-ferry consumption (kWh)*	LMG-50.1	LMG-50.1 consumption (kWh)**
Propulsion energy used by engines	5 return trips, electricity	8,097	5 return trips, marine fuel	7,925
Energy used for hotel load in operation	55 kW during sailing and in Fynshav harbor	597	110 kW during sailing, 100 kW in Søby and Fynshav harbor, marine fuel	1,170
Idle time/land power	10 hours hotel load consumption (55 kW) night time and hotel load consumption during charging in Søby, total 12.5 hours, electricity	747	11 hours idle time/hotel load consumption from shore power, 100kW electricity	1,195.6
Total consumption, electricity		9,442		1,195
Total consumption, marine fuel		N/A		9,095

** Including an efficiency of 0.92 between the battery and the propeller and 0.95 between the charging (grid) and the batteries.*
*** Including an efficiency of 0.92 for the generator and 0.94 between the diesel engine and the generator*

Different factors may influence the SFOC, including sea and air inlet temperatures that may influence the performance of the engine and increase the SFOC by 5-8 % (Dedes et al. 2011), moreover the SFOC will also increase over time, as the engine is worn. For example, the fuel consumption on a traditional diesel vessel, has increased from 4,200 to 4,800 liters per day, over a period of 20 years (i.e., an increase of 14.3 %) (Aeroe-ferries 2020). As other factors (e.g., increased weight) may influence the overall use of fuel over time, a conservative 5 % increase for the Wärtsilä 16V14 engine is considered to reflect both the potential increase due to real operation conditions and to reflect the overtime deterioration that would be expected. The minimum reference point (i.e., the consumption of marine fuel per produced kWh for the diesel motors at optimal 80 % load) for the LMG-50.1 is estimated to be 215.3 g/kWh, and for the Wärtsilä 16V14 engine equals to around 972 kW per genset (Heinemann et al. 2020).

The LMG-50.1 when travelling at sea speed of about 12.5 knots, has a total power demand of 960 kW (i.e., 480 kW for each diesel generator; the LMG-50.1 carries 2 diesel Wartsila 16V14 generators). When taking into account losses from genset to engine (i.e., factor of 0.92) and losses from diesel motor to transformer (i.e., factor of 0.94), the total power load demand per genset is estimated to be 555 kW or 1,110kW in total (i.e., 960÷0.92÷0.94).

Therefore, the highest power load demand per genset is roughly 555 kW, which is almost half of its rated power and below the SFOC' reference point. For the LMG-50.1 an initial SFOC of 215.3 g/kWh at 80 % engine power load, is converted to 221.8 g/kWh SFOC based on the assumption that at a sea speed of 12.5 knots, the SFOC is 3 % higher (Dedes et al. 2011). Moreover, based on E-ferry collected data for a return trip, it is estimated that for 17 minutes of manoeuvring in ports 135.2 kWh (i.e., SFOC od 350 g/kWh) are consumed and for loading/unloading in ports the energy consumption is 53.2 kWh (i.e., SFOC of 250g/kWh). The daily consumption of LSMGO<0,1 % marine fuel is 430.4 kg.

3.4.3. Diesel-vessel

Energy consumption cost for the M/F Marstal is calculated similar to the LMG-50.1. The M/F Marstal sails 5 trips in 13 hours, between Søby and Fynshav. The supplied on-shore power during the 11 idling (night) hours, with an expected hotel load of 130 kW is included. The M/F Marstal has less energy efficient design and less energy efficient diesel engines, leading to higher fuel costs per day and year, compared to the LMG-50.1. To obtain the maximum required speed, the energy demand for the M/F Marstal's genset will be 1,787 kW, rather than 1,110 kW required for the LMG-50.1 (both including losses). Similarly, the hotel load for the M/F Marstal is 130 kW, which is higher than that of the LMG-50.1. The overall fuel consumption for the M/F Marstal is higher compared to the LMG-50.1, due to the inefficient energy design and the inefficient diesel engine. The consumption in kWh or g/kWh and the LSMG<0.1 % requirements (in kg) per return trip on the Søby-Fynshav route, for the ferry propulsion is 2,018.8 kWh or 179g/kWh (522.5 kg), the hotel load at sea is 254.8 kWh or 179 g/kWh (45.6kg), the hotel load at port is 65 kWh or (35.8 kg) and for the manoeuvring is 171.8 kWh or 320 g/kWh (55kg).

For the final calculation of marine fuel costs for diesel vessels, the average monthly price of 635 €/metric ton has been used (including partial VAT as paid by the operator). For the land electricity supply during night time, the Danish electricity price of 0.0711 €/kWh (including a fee for green electricity) is used. Table 5 presents the final estimations for all energy costs.

3.5. General Costs

The general cost, include maintenance, repair, dockings and survey costs. These have been estimated for a five-year period, and then distributed over the period of five years. Other considered costs are: insurance (ship and shore), Value Added Tax (VAT), other taxes and fees. Annual general costs for operating each vessel for five trips per day are shown in Table 5 (rounded to the nearest thousand).

Table 5.
Summary of annual costs per vessel type.

Cost category	Cost description	Cost €
E-ferry		
Operating crew costs	3 crew (incl. 2 navigators and 1 catering crew, 14h shift per day). Total crew required per month 3x3. Incl. salary fee.	886,000
Supporting crew	One engineer/technician, full time (155 hours per month), one able body/ maintenance crew, 48 hours per month. Incl. salary fee.	121,000
Energy cons. operation	Actual energy use for 14 hours of operation, incl. hotel consumption during harbor docking in Fynshav (8,695.7 kWh/ day)	222,000
Energy cons. idling	Actual energy use for 12.5 hours of idling in port Søby incl. hotel consumption (747.3 kWh/day)	19,000
Maintenance	Repair and replacement costs, dockings, surveys and service	228,000

Insurance	Ship and shore	79,000
Other expenses	Operation and maintenance of ramps, various crew expenses, ticketing equipment, shore supply for idle hours etc.	158,000
Total cost	Annual (5 trips per day, 360 days per year)	1,714,000
LMG-50.1		
Operating crew costs	4 crew, as approved, including two navigators and a catering crew with safety papers, and an engineer, 13 hours shift per day.	1,129,000
Energy cons. operation	Actual energy use (marine fuel) for 13h of operation, incl. hotel consumption during harbor stays, provided by diesel-electric engine (2.15 metric ton/day)	492,000
Energy cons. idling	Actual energy use (electricity) for 11h idling (night), with hotel consumption, provided by on-shore electricity (1,195.6 kWh/day)	31,000
Maintenance	Maintenance, service and repair on ship and charging system, surveys, dockings	365,000
Insurance	Ship	64,000
Other expenses	Maintenance of on-shore installations (ramp, auto mooring etc.), crew expenses, ticketing equipment etc. excl. night on-shore power supply	175,000
Total costs	Annual (5 trips per day, 360 days per year)	2,256,000
M/F Marstal		
Operating crew costs	5 crew, incl. two navigators, a chief engineer, an able seaman and a catering crew, 13 hours shift per day.	1,310,000
Energy cons. operation	Actual energy use (marine fuel) for 13h of operation, including hotel consumption during harbor stays, provided by diesel genset engine (3.3 metric ton/day)	745,000
Energy cons. idling	Actual energy use (electricity) for 11h of idle time (night), with hotel consumption, provided by on-shore electricity (1,430 kWh/day)	37,000
Maintenance	Maintenance, service and repair on ship and charging system, surveys, dockings	365,000
Insurance	Ship	64,000
Other expenses	Maintenance of on-shore installations (ramp, auto mooring etc.), crew expenses, ticketing equipment etc. excl. night on-shore power supply	169,000
Total costs	Per year, for operation with five trips a day	2,690,000

3.6. Battery Replacement

For the E-ferry, the battery end-of-life has been determined to be when the overall State of Charge (SoC) capacity reaches at 80 %. In principle, this decrease in the battery capacity over time, could be accommodated by changing the operation schedule, including longer charging breaks, but this is often not a commercially viable solution.

The expected life-time of batteries for the E-ferry, based on its performance characteristics at the current operation schedule, is around 12 years. (i.e., 39 % average depth of discharge, 24,500 cycles to SoC 80 % are 12 years, 1,600 kWh average energy flow, 39,200,000 kWh life time flow in sailing operation and 11.74 years in sailing schedule). As there is no long-term empirical data available yet to confirm the number of cycles applicable for maritime batteries, the exact timing of when the E-ferry prototype battery pack will reach 80 % SoC capacity is highly uncertain.

Cells have been cycled in laboratory tests and the theoretical numbers are extrapolated. Moreover, it could turn out to be a better solution to see replacement of batteries as a maintenance task, where single modules and parts of systems are replaced and/or repaired on a running basis. As these are as yet unknown factors, the cost estimations for the E-ferry prototype in this paper, are based on the assumption that the whole battery pack, including Battery Management System (BMS) and other systems (e.g., firefighting). Figure 2 shows collected and forecasted data for the battery system (Heinemann et al., 2020).

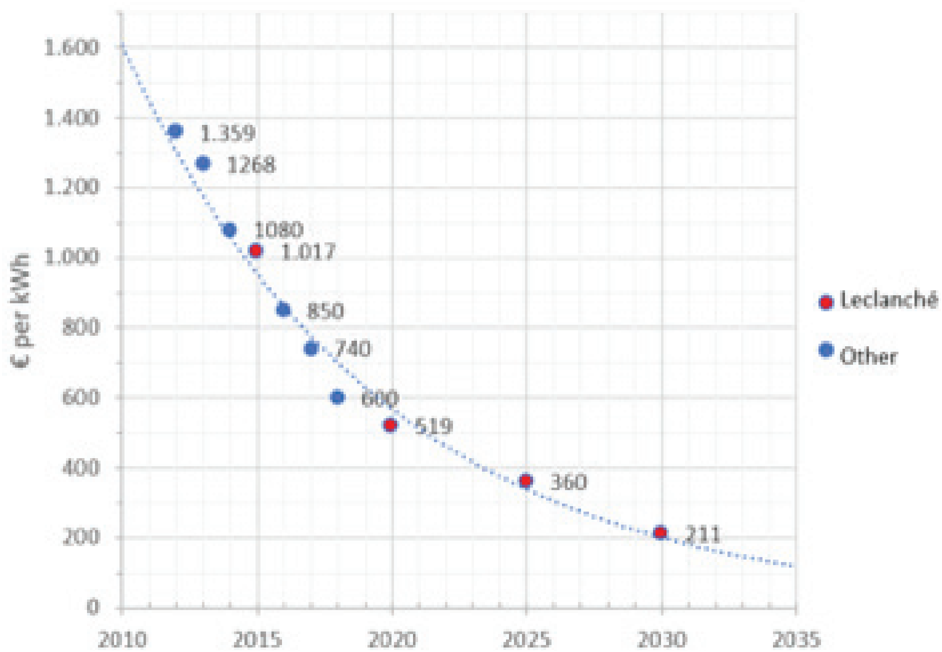


Figure 2.
Battery system cost actual and forecasted data.

Therefore, the cost estimations for the E-ferry prototype are based on the assumption that the whole battery pack, will be replaced twice, in year 12 and 24 (although the battery lifetime is expected to be improved for the second array of batteries). The cost for maritime battery packs has been forecasted to be 519 €/kWh in 2020, 360 €/kWh in 2025, and 180 €/kWh in 2032. The battery system costs 2.1 million euros (2020) and 731,700 € (2032).

4. RESULTS AND DISCUSSION

In addition to the construction and operation-based costs of the E-ferry, the construction cost of a third E-ferry vessel (series 3) was estimated, excluding the prototype development costs and by using the current battery cost (year 2020). Two conventional ferries have been selected to complete the economic evaluation: a new built diesel-electric vessel (the LMG-50.1) and an existing, older vessel (the M/F Marstal). The costs of these four ferries are presented in Table 6. For the E-ferry prototype and the E-ferry series 3, development costs are excluded, and costs for auto mooring for two harbors are included. Similarly, for the LMG-50.1 costs for auto mooring in two harbors are included. Finally, for the M/F Marstal auto mooring costs are excluded. The construction costs for each vessel are shown in bold in Table 6.

All operation costs include relevant taxes and are presented on an annual basis, for each vessel the costs are based on an operation schedule with five return trips. Given that the E-ferry operates in Denmark, the tax regulations that are considered here are imposed in the specific country. Denmark is a country with a high Gross Domestic Product (GDP) and showing significant environmental sensitivity. These two aspects are depicted in the wages (the former) and in the taxes imposed on renewable energy sources and environmentally friendly solutions (the latter).

Table 6.
Summary of construction and operation costs in 2020€ per vessel.

		(a) E-Ferry plan		
	E-ferry prototype	E-ferry series 3	LMG-50.1	M/F Marstal
Cost of ferry	16,662,000	13,250,000	13,000,000	12,856,000
Cost of shore charging system	2,452,000	2,345,000	n/a	n/a
Cost excluding development costs	18,493,000	n/a	n/a	n/a
Cost including auto mooring for 2 harbors	19,640,000	16,742,000	14,147,000	n/a
Operation costs/year (5 trips/ day - 360 days/year)	1,714,000	1,714,000	2,256,000	2,690,000
		(b) Grid transformer ownership plan		
	E-ferry prototype	E-ferry series 3	LMG-50.1	M/F Marstal
Cost of ferry	16,662,000	13,250,000	13,000,000	12,856,000
Cost of shore charging system	2,452,000	1,858,000	n/a	n/a
Cost excluding development costs	18,493,000	n/a	n/a	n/a
Cost including auto mooring for 2 harbors	19,640,000	16,742,000	14,147,000	n/a
Operation costs/year (5 trips/ day - 360 days/year)	1,714,000	1,671,000	2,256,000	2,690,000

As anticipated, the investment cost is 15 %, 28 % and 35 % lower for the E-ferry series.3, the LMG-50.1, and the M/F Marstal, respectively, compared to the E-ferry prototype (Table 6a). As shown in Table 6a, the construction cost of a third new E-ferry would be significantly reduced compared to the E-ferry prototype; in terms of construction costs the cost for a fully electric ferry (series 3) is higher by 16 % and 23 % compared to the LMG-50.1 and the M/F Marstal, respectively. In other words, as battery cost decrease, the main economic difference between a fully electric and a conventional vessel, will be the supporting infrastructure and the connection fees required to access the on-shore grid.

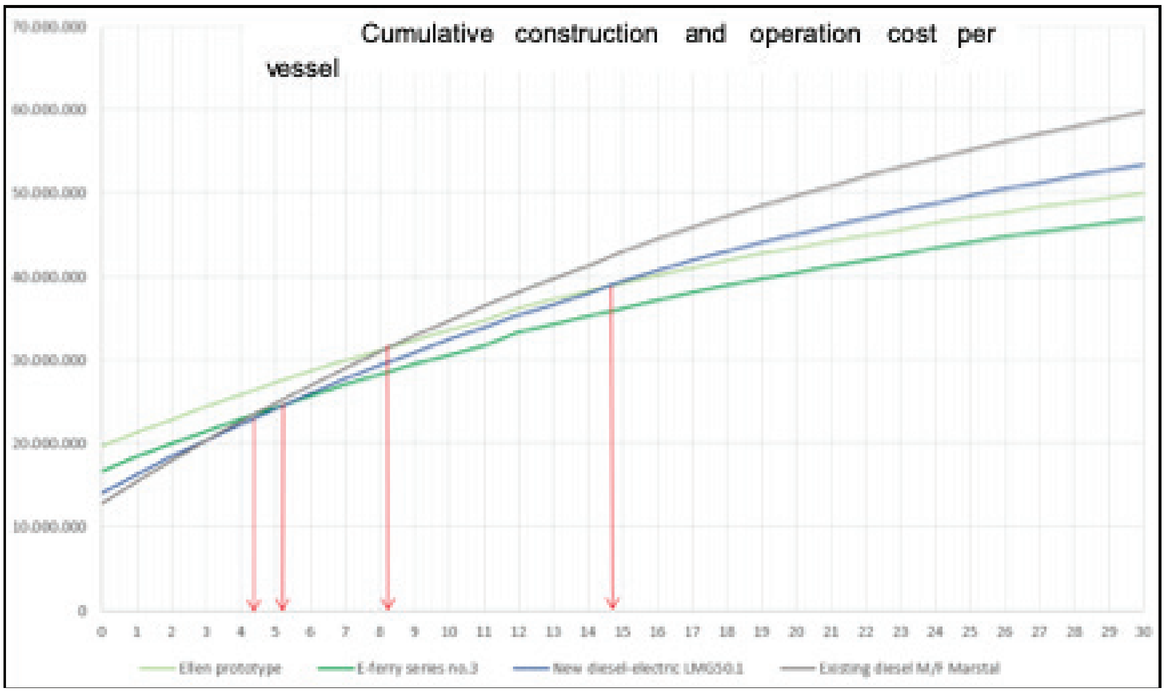
In terms of operation costs, both E-ferries (i.e., prototype & series 3) provide 24 % and 36 % savings compared to the LMG-50.1 and the M/F Marstal, respectively. Operation costs refer to the annual expanses and they are assumed to be stable in the lifetime of the vessel, as opposed to the construction costs that are a one-off investment. The lifetime of the vessels is assumed to be 30 years, which is normal practice for ferry operators.

For both E-ferries, one of the most significant impacts in the evaluation is the higher investment for the battery and the on-shore charging infrastructure. The battery cost for maritime applications is forecasted to decrease significantly over the next years, thus eliminating a substantial amount of up-front costs for electrical ferries. Reducing the up-front costs (as well as further reducing energy costs) can be achieved by an alternative ownership plan of the charging transformer station. Under this plan, the operator builds, owns and operates the 10kVA grid transformer directly. In this case, the cost of the charging system would be reduced by 21 %, as the one-time connection fee is substituted by the investment cost of the high voltage cabling and transformers (Table 6b). Building and operating the 10kVA grid transformer directly – in the Danish grid and energy regulations – entail that the E-ferry operator would be categorized as a B-high, rather than B-low customer, which would result in a reduction of 12 % in energy costs including VAT (i.e., 3 % in overall operation costs)[1]. Table 6b summarizes the potential savings on the investment costs for E-ferry series 3, by using the grid ownership plan.

Replacing major components over a ferry's lifetime (i.e., 30 years or more), should be considered when deciding whether to invest in an electric ferry opposed to a conventional diesel or a diesel-electric ferry. The cost for replacing the battery system on both E-ferries is considered in years 12 and year 24. A replacement or major overhaul/upgrade of the equivalent diesel engine and the generator has been added to both conventional vessels, in year 15 at a cost of 500,000€, in accordance with practice.

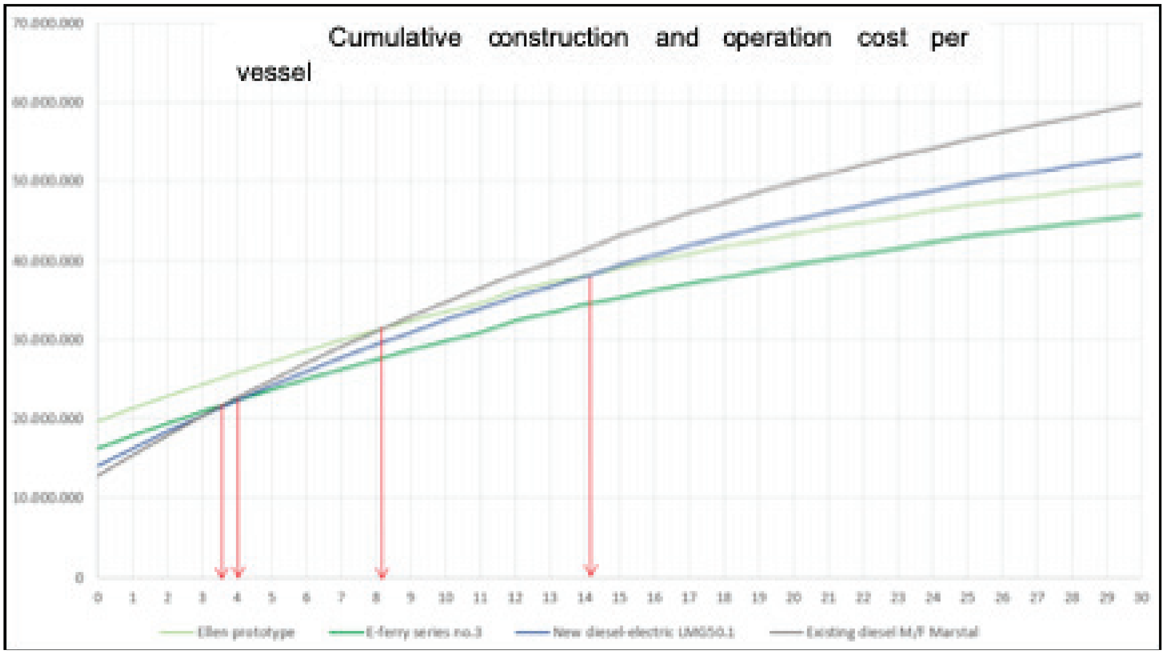
The method applies an internal annual discount rate of 4 % to discount future costs to present value. The results show that the E-ferry series 3 achieves cost parity with the LMG50.1 and the M/F Marstal in 5.2 years and 4.3 years, respectively. The E-ferry prototype achieves cost parity with the LMG50.1 and the M/F Marstal in 15 years and 8 years, respectively (Figure 3a).

When considering the Grid transformer ownership plan (Figure 3b), the cost parity for the E-ferry series 3 is achieved after 4.0 and 3.6 years with the LMG50.1 and the M/F Marstal, respectively, which is 9-14 months earlier compared to the E-ferry plan. Energy policies have the potential to provide incentives to operators and expedite the cost parity period between investments, which becomes essential in energy and transportation related projects with high initial capital investments.



a)

1. *Two cost schemes exist in Denmark for electricity prices: B-low and B-high. Under B-high scheme the VAT is reduced by 12 %*



b)

Figure 3.
Cost parity (€) between the four vessels for 30 years lifetime;
a) Using the E-ferry plan, b) Grid transformer ownership plan.

5. CONCLUSIONS

The European Monitoring and Evaluation Programme has estimated that about 90 % of the NOx and SO2 ship emissions in the North Sea originates from a zone of only 50 Nm from the coast line. Therefore, the ferry routes may be extremely suitable for implementing electric ferries due to their fixed time and route schedules (Tsyro and Berge 1997).

The economic evaluation has concluded that the E-ferry prototype is a valid commercial alternative from a purely economic aspect. Thus, while the E-ferry prototype in particular has higher construction costs, its operation costs, especially those dedicated to energy/fuel, are significantly lower, and result to a pay-back period of 5-8 years of operation. Similarly, while battery systems have been a major cost contributor for the E-ferry, the steady decrease of battery cost promotes the fully electric vessels as a sustainable alternative. Another main contributor to the total cost of the E-ferry prototype is the supporting charging system. Future E-ferries should preferably be constructed by following different ownership plans, which would lead to lower one-time investment costs and electricity savings.

At present, a mature market for turning over used battery cells and battery banks does not exist. Future research may show a viable business case, to provide a better valuation of used battery cells from maritime applications, but for now, uncertainties are high, and the consideration of used batteries has not been included in the overall economic evaluation.

The environmental benefits of operating an electric ferry are expected to be more prominent. Considering and monetizing CO2 savings by using a rate of 20€ per ton CO2-equivalent, it would add another 135,136€ and 498,067€ annually to the operation costs of the LMG50.1 and the M/F Marstal, respectively. Moreover, energy incentives and plans to operators will likely increase future demand for electric ferries. Electric ferries have the potential to dramatically change the cost of ferry operations by considering direct and indirect costs, such as emissions, noise and wave generation.

CONFLICT OF INTEREST:

There is no conflict of interest.

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