E-Ferry Project

Prototype and full-scale demonstration of next-generation 100% electrically powered ferry for passengers and vehicles

Evaluation report of the E-Ferry

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Contents

1 Introduction

E-ferry is a research project funded under the EU HORIZON 2020 Initiative (Grant agreement number 636027). It addresses the urgent need for reducing European CO_2 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 main objectives of the project were:

1. To **design** and **build** an innovative vessel that is 100% electric and where the main characteristics are energy efficient design, incorporation of lightweight equipment and materials, and state-of-the-art electric only systems with automated high-power charging system.
2. To **validate** the feasibility and cost effectiveness of the concept to the industry and ferry operators through demonstrating the vessel's ability to cover distances of up to 22 nautical miles on connection(s) in the Danish part of the Baltic Sea that are currently operated by conventional diesel driven vessels.

The E-ferry prototype was designed, constructed and approved by relevant authorities during the project period from June 2015 to June 2019. Following the completion and final approvals, it was handed over to the operator AEROE-ferries, who – after a training period of about 6 weeks - put the E-ferry into ordinary operation on the route from Søby-Fynshav in the Southern part of Denmark, on August 15, 2019. By the conclusion of this report (Medio May 2020), the E-ferry prototype has been sailing as an ordinary car- and passenger ferry, including a trial period, for 10 months and a total of approximately 1000 return trips, each of 22 nautical miles, between Søby and Fynshav. The current report provides an evaluation of the technical, economic, environmental and societal impact that the implementation of the E-ferry prototype has had, during this period, and beyond. The report is intended to provide the ship industry, operators, policy makers and other interested parties with a reliable and empirical presentation of the E-ferry prototype's performance in comparison to conventional diesel-driven ferries, and to confirm that fully electric ferries constitute a valid alternative to more conventional ferry types, not only environmentally, but also technologically and economically.

The overall report is organized as follows: First, we present the E-ferry prototype, its main specifications, technical details and the basis for the E-ferry classification and flag approval (Section 2). We then provide details about the operation of the E-ferry, including operation area, onshore facilities, as well as operation schedule throughout the period investigated (Section 3). Section 4 presents the overall evaluation and validation of the E-ferry prototype and is separated into 4 subsections, each detailing the 4 different evaluations; the E-ferry technical Evaluation, E-ferry economical evaluation, Environmental evaluation, and Societal evaluation. We conclude the report by highlighting the main important points and findings from the overall E-ferry evaluations in **Results and conclusions**.

2 The E-ferry Prototype

2.1 General particulars

Figure 1: **The E-ferry prototype**

The E-ferry prototype is a small/medium sized single-ended Ro-Pax ferry. Main particulars are listed in **Error! Reference source not found.**, General Arrangement is illustrated in Figure 2.

Table 1: Main Particulars of the E-ferry prototype

Principal dimensions	
Length, oa	59,4 m.
Length, bp	57 m.
Breadth, moulded	12,8 m.
Depth, moulded	3,70 m.
Gross tonnage	996
Displacement	933 t.
Design, draught	2,5 m.
Design, deadweight	187 t.
Lightweight	746 t.
Deck space	458 m^2
Deck capacity	1,75 t/m^2
Service speed	13,5 kn.
Max speed	14,2 kn.
Capacity and crew	
Lane length vehicle deck	145 m.
Number of cars	31
Number of trucks/trailers	5
Number of passengers	147/196
Number of crew	3/4
Power and propulsion	
Main engines	2x700 kW
Thruster engines	2x250 kW
Nominal battery capacity	4.3 MWh
Charging effect	4 MW
Classification and approvals	
Flag	Denmark
Approval basis	DMA Notice D, RO Directive 2009/15EC, RO regulation (EC) 391/2009, SOLAS Chapter II-2, IMO MSC.1/Circ. 1455
Classification society	DNV GL

Notations	1A1 Car ferry B, Battery(Power), E0, Ice©, PWDK R3

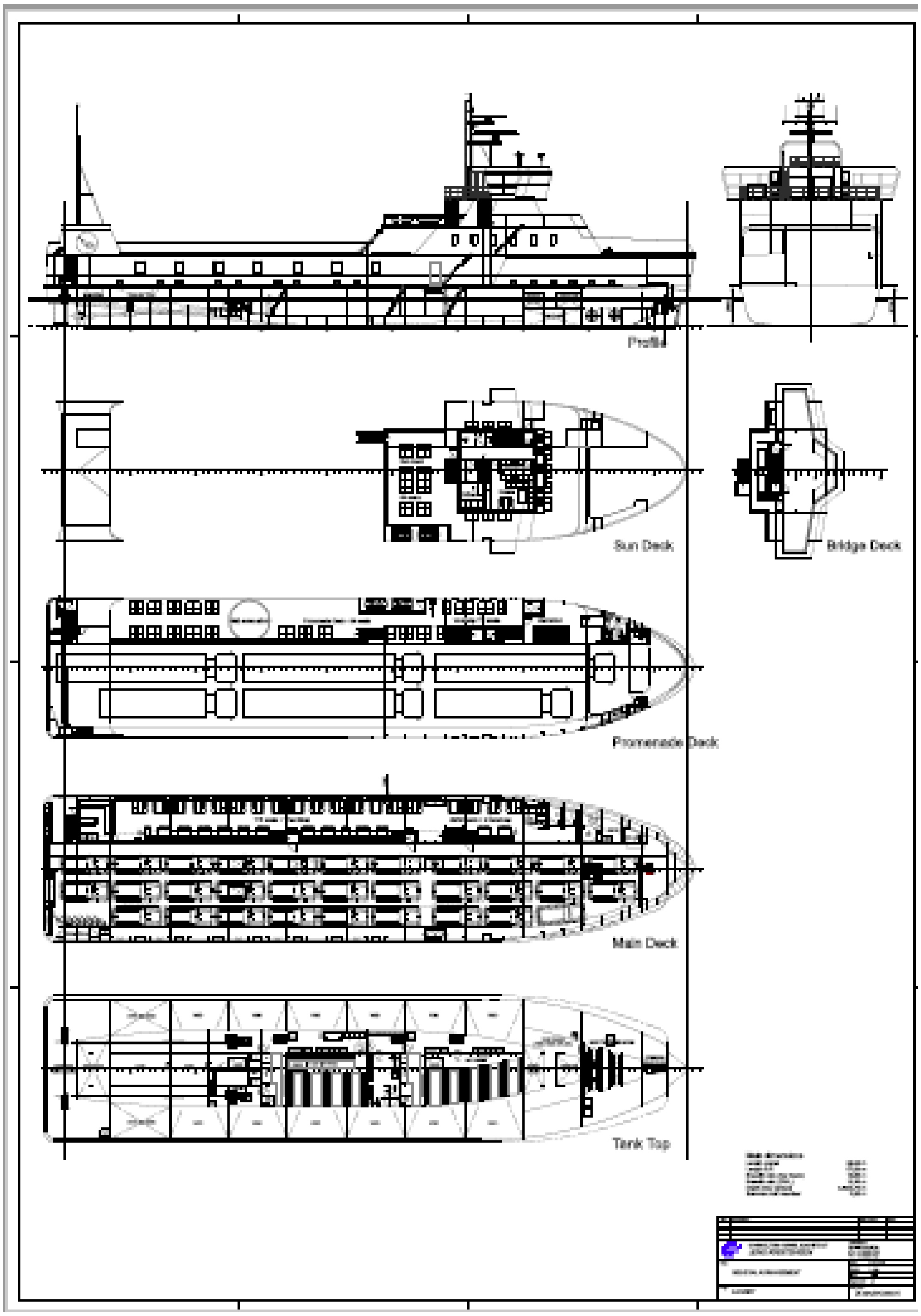


Figure 2: **General arrangement of the E-Ferry prototype**

2.2 The E-ferry electric system and charging

As indicated in table 1, the E-ferry battery capacity has the nominal value of 4.3MWh and can be charged with an effect of up to 4 MW. The dimensioning of the battery capacity and charging effect have been based on the operator's requirements for ordinary ferry operation on a route up to 22 nautical miles (e.g. Søby-Fynshav-Søby, see Section 3 for more details) and with up to 7 trips a day within the operating hours of 06:00-24:00. Moreover, as the E-ferry is fully electric and has no back up emergency generator, a capacity of 2x400 kWh has to be reserved at all times for emergency purposes.

The E-ferry system is designed and dimensioned so that the E-ferry prototype should use an estimate of just over 1/3 of its nominal capacity (1600 kWh) on a trip of 22 nautical miles and charge a little less (1100-1300 kWh) than what has been used on a trip during the 20-35-minute harbour stays. This means that the E-ferry leaves the charging harbour for the first trip in the morning fully charged, but gradually over the day diminishes its charged capacity, so that by the end of the day it will be around 30% of its nominal capacity. Figure 3 illustrates the simulated values that have been calculated for the E-ferry dimensioning of battery capacity and charging effect (see Section 5.1.5 for the actual values based on the different operation schedules tested during the evaluation period).

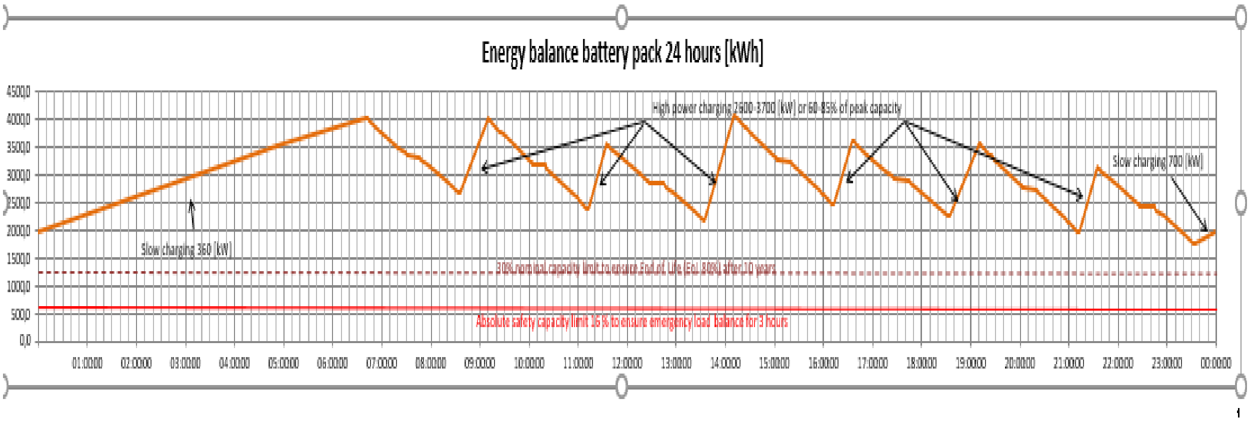


***Figure 3*: E-ferry energy balance and charging profile**

3 E-ferry operation

3.1 E-ferry route profile

The E-ferry prototype operator, AEROE-ferries has received approval by the Danish Maritime Authorities to operate the E-ferry in the Southern Danish area of the Baltic Sea, on the routes Søby-Fynshav and Søby-Faaborg. The distance for each of these routes are each just below 22 nautical miles (return trip), with the route from Søby-Fynshav being slightly longer than the route from Søby-Faaborg. For that reason, the evaluation of the E-ferry prototype in operation has - during the period from July 2019 to May 2020 - focused exclusively on the longer (and hence more challenging) route from Søby-Fynshav. Figure 4 below illustrates the operation area and the two routes with approval from the Danish Maritime Authority to operate the E-ferry prototype.

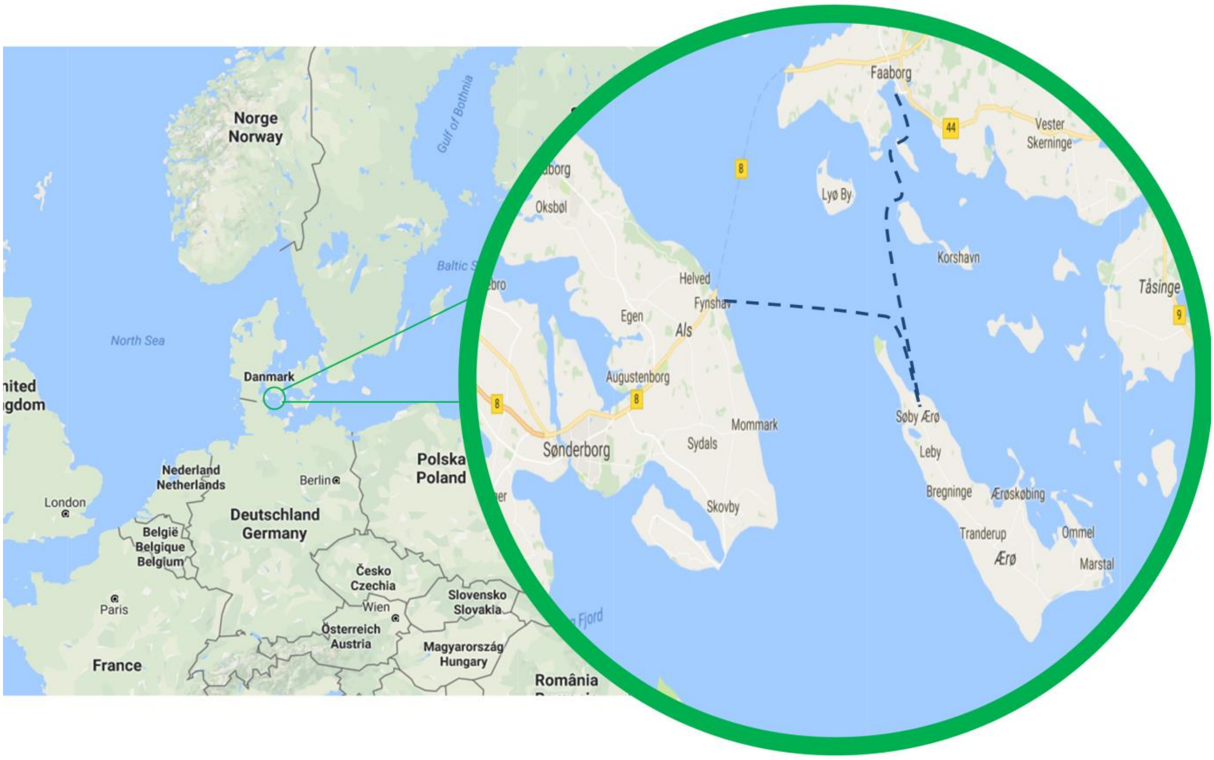


***Figure 4*: E-ferry operation area**

On-shore facilities for the E-ferry prototype have been prepared in each of the three harbours between which the E-ferry can operate, i.e. Søby, Fynshav and Faaborg. Each of the harbours has been equipped with an automated mooring system, for faster docking and less crew work. Charging is only possible, however, in the E-ferry prototype's home harbour of Søby, for which reason the harbour stays in Søby are typically longer than those in Fynshav and Faaborg. The E-ferry prototype charging system is a semi-automated plug-connection, placed on the on-shore ramp and hence charging from the fore end of the ferry, as illustrated in Figure 5.

***Figure 5*: E-ferry charging system**

3.2 E-ferry operation schedule

During the trial and evaluation period, starting from July 3, 2019, the E-ferry has been tested and evaluated under different conditions and operating schedules. Table 2 provides a general overview of the various schedules and operation profiles that have been implemented during the 10 months evaluation period.

***Table 2*: Operation profiles for E-ferry prototype in evaluation period**

Period No	Period	Type of operation	Number of trips per day
1. Training	July 3-August 15, 2019	Training for crew and operator approval	0-3
2. Test operation	August 15-September 8, 2019	Ordinary operation	3-4
3. No operation	September 8-September 15, 2019	No operation due to technical problems	0
4. Test operation	September 15-November 11, 2019	Ordinary operation	3-4
5. No operation	November 11-November 29, 2019	No operation due to optimization work	0
6. Optimized operation	November 30, 2019 – February 29, 2020	Ordinary operation	4
7. Increased operation	March 1 – May 31	Ordinary operation	5-6

For the sake of future easy reference, each of the periods have been numbered and named. During each of the periods, the overall operation schedule of the E-ferry varied. This reflects the status of each period: during period 2 and 4, which we have labelled test operation, the port stays in the charging harbour were generous to allow for mitigation of any technical problems and/or delays, just as the sailing time from port to port included a buffer to allow crew to get used to manoeuvring the vessel and to ensure that the energy consumption was within the required safety levels. Time of port stays and sailing time was gradually decreased over period 4, as the crew got more familiar with operating the vessel and the technology as a whole became more reliable. After technical adjustments to Battery Management System and propellers had been implemented (in period 5), these adjustments were similarly tried and tested over a period of three months (period 6) before the operation schedule was increased (with port stays, charging time and sailing time consequently being reduced) during period 7.

Table 3lists the different operation schedules that have been implemented during the overall evaluation period, and explains the schedule use for each operation period. **Error! Reference source not found.** below provides the details of the operation schedule for period 7, directly from the operator, Aeroe-ferries web-page (https://www.aeroe-ferry.dk/da/sejlplaner/sejlplaner-01-03-16-12-2020):

***Table 3*: Operation schedule for the E-ferry prototype in the evaluation period**

Number of trips	Sailing time	Port stay/charging time	Period
3	70 minutes	>one hour	2
4	60 minutes	45-80 minutes	2+4+6
5-6	55-60 minutes	20-75 minutes	7

Søby > Fynshav

Overfartstid 60 min.

Man-fre.	Lørdag	Søndag & H. +5/6-20
06:00	06:00	
08:30	08:30	08:30
11:20	11:20	11:20
14:15	14:15	14:15
17:05	17:05	17:05
h) 19:35		19:35

h) Sejler kun fredage i perioden 29/5 - 16/10-2020 inkl.

Fynshav > Søby

Overfartstid 55 min.

Man-fre.	Lørdag	Søndag & H. +5/6-20
07:10	07:10	
09:45	09:45	09:45
12:35	12:35	12:35
15:30	15:30	15:30
18:20	18:20	18:20
h) 20:50		20:50

h) Sejler kun fredage i perioden 29/5 - 16/10-2020 inkl.

***Figure 6*: Operating schedule of the E-ferry prototype, period 7.**

4 Evaluation

The overall Evaluation Framework for the E-ferry prototype covers four broader areas, as follows:

(a) Technical Evaluation: to assess and validate the E-ferry overall performance, e.g. in terms of reliability, energy efficiency, energy use, speed, manoeuvrability, frequency and distance.

(b) Environmental Evaluation: to assess the achieved reductions in various environmental pollutants that have been gained by implementing the E-ferry, including an assessment of environmental effects when considering the full life cycle of the vessel as compared to similar vessels with diesel-electric or fully diesel-driven propulsion.

(c) Economic Evaluation: to assess the overall construction and operation costs of the E-ferry, in comparison with similar vessels with diesel-electric or fully diesel-driven propulsion.

(d) Societal Evaluation: to assess any impacts the E-ferry has had on the wider society and in particular on its users and producers.

The overall Evaluation Framework for the E-ferry prototype is illustrated in Figure 7, below.

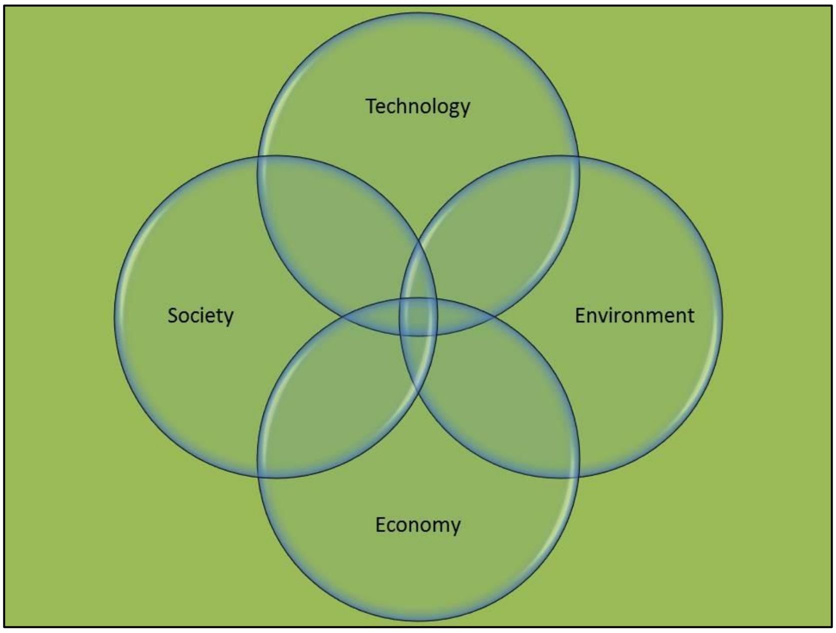


***Figure 7*: The Evaluation Framework for the E-ferry prototype**

As illustrated in Figure 7, the various pillars of evaluation of the E-ferry prototype are in effect intertwined and each may impact the other. As the overall functionality and operationality of the E-ferry technology, however, lays the basic groundwork for all other evaluations, we begin with describing the overall functionality of the E-ferry prototype, i.e. how it has performed during the various stages of the demonstration/evaluation period. We then turn to the E-ferry economical evaluation, specifying both the construction and operational costs of the E-ferry prototype, and comparing these to two alternative solutions for a ferry operator, a new built conventional diesel-electric ferry of similar type and capacity as the E-ferry prototype, and an existing older vessel which could at least in theory be operated on the same route(s) as the E-ferry prototype (Section 5.3.5). Following this, we present the Environmental evaluation in the framework of which the E-ferry performance is also compared to the two alternative vessels with respect to their respective environmental impacts, e.g. in terms of emissions, both in operation and over the full life-cycle of a ferry (Section 5.4). We conclude with the E-ferry Societal evaluation, in which the impact on both users and industry is evaluated Section 5.5). For each evaluation section, a respective table of indicators will be used to summarize the overall findings.

5 E-ferry technical Evaluation

5.1 Methodology and data

For the technical evaluation of the E-ferry prototype, data from various sources have been implemented and analysed, including Technical performance data, Load and transport statistics and Weather and oceanographic data. Rationale, methodology and parameters for the data collected is described below:

5.1.1 Technical performance data

The technical performance data has been collected directly via the E-ferry's Integrated Automation System, where the Valmet DNA continuously logs all tagged data at specified time-intervals. *Figure 8* provides a schematic overview of the IAS and its data logging features.

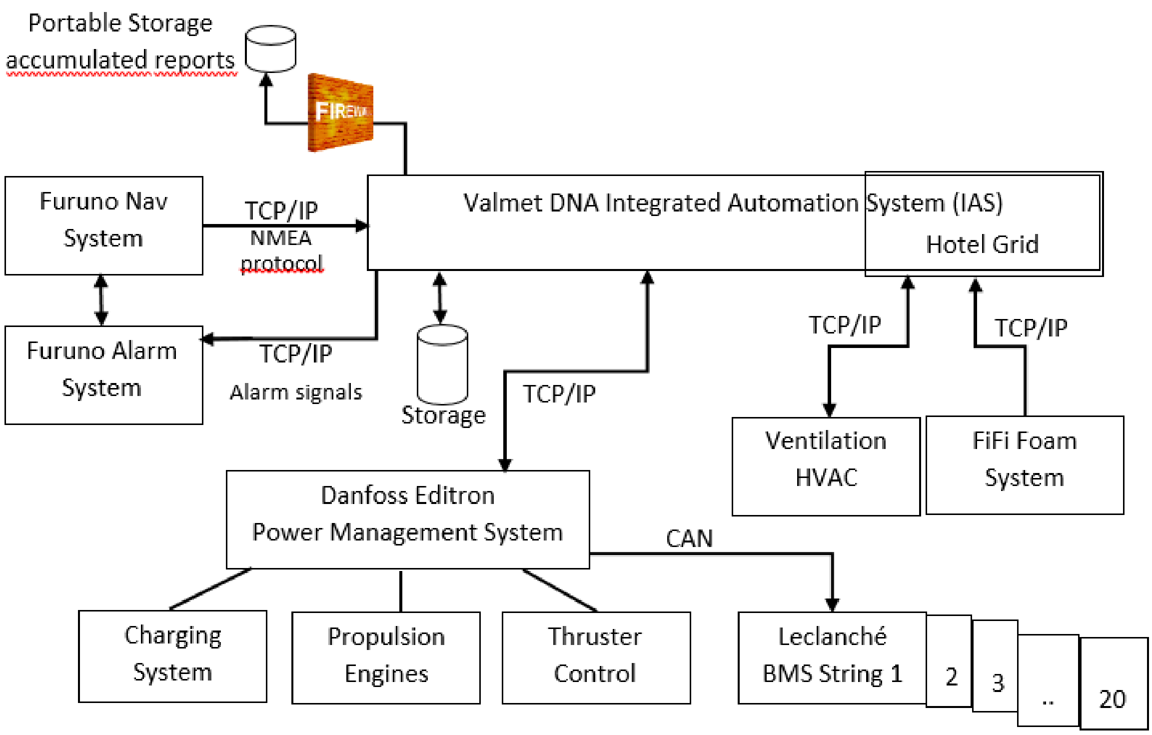


Figure 8: Schematic overview of the Integrated Automation System and its data logging features

As illustrated in Figure 8, the data logging system on board the E-ferry collects both technical data, such as energy consumption, energy capacity, power usage and charging data, as well as what we term navigational and/or operational data, such as draught, rate of turn, position and speed. This data is continuously logged in the IAS, and subsequently extracted manually, via the Valmet DNA program, into an excel sheet, where values for each of the parameters are provided per minute. Figure 9 below illustrates a fraction of the parameters extracted as of November 1, 2019. As can be seen from this, the parameter for speed was not logged at this time, due to a fault in the system registering this (Furuno Nav system as indicated in Figure *8*, upper left hand corner). Overall, through the evaluation period, all data for all systems was logged, however, with only smaller periodical glitches such as this.

	COG:av	HEADING:av	LATITUDE:av	LONGITUDE:av	LONGITUDINAL_SPEED:av	RATE_OF_TURN:av	SOG:av	SOUNDER_DEPTH:av	TRANSVERSE_SPEED:av	WIND_DIRECTION:av
	COG	HEADING	LATITUDE	LONGITUDE	LONGITUDINAL_SPEED	RATE_OF_TURN	SOG	SOUNDER_DEPTH	TRANSVERSE_SPEED	WIND_DIRECTION
Time	deg	deg	deg	deg	knots	°/min	knots	m	knots	deg
01-11-2019 07.13.01	279,5884094	276,9603882	5459,21582	1003,150085	0	-0,38166666	11,41988277	31,68020058	0	242,5966644
01-11-2019 07.14.01	279,5523987	276,9482727	5459,269043	1002,905945	0	2,000666618	11,4081049	31,86237335	0	235,6199951
01-11-2019 07.15.01	279,5163879	276,9361572	5459,322754	1002,661743	0	0,066166721	11,39632702	32,04542542	0	244,4250031
01-11-2019 07.16.01	279,4804077	276,9240417	5459,376465	1002,417603	0	-0,922666669	11,38454819	32,22847366	0	245,0200043
01-11-2019 07.17.01	279,444397	276,9119263	5459,430176	1002,173462	0	-0,555999994	11,37277031	32,41148376	0	245,4850006
01-11-2019 07.18.01	279,1044006	276,1253052	5459,483398	1001,92926	0	-1,529166698	11,36099243	32,44363785	0	236,9799957
01-11-2019 07.19.01	277,5388489	275,1540833	5459,537109	1001,68512	0	1,568000078	11,3492136	32,33454514	0	243,3899994

***Figure 9*: Fragment of data extracted for November 1st, 2019**

The full set of parameters extracted via the Valmet DNA is listed in Table 4, with indication of the nature of the data, i.e. whether it is technical or navigational/operational data:

***Table 4*: Data parameters and values logged and extracted via the Valmet DNA**

Parameter	Value	Data type
Course over ground (COG)	degrees	Navigational
Heading	degrees	Navigational
Latitude	degrees	Navigational
Longitude	degrees	Navigational
Longitudal speed	knots	Navigational
Rate of turn	degrees/minute	Navigational
Speed over ground (SOG)	knots	Navigational
Transverse speed	knots	Navigational
Sounder depth	meters	Navigational
Depth measurement fore	meters	Navigational
Depth measurement aft	meters	Navigational
Wind direction	degrees	Navigational
Wind speed	knots	Navigational
Starboard PMS available energy	%	Technical
Portside PMS available energy	%	Technical

Starboard PMS available power	kW	Technical
Portside PMS available power	kW	Technical
Starboard PMS available energy	kWh	Technical
Portside PMS available energy	kWh	Technical
Starboard BAT SOC	%	Technical
Portside BAT SOC	%	Technical
AC Starboard Hotel power	kW	Technical
AC Portside Hotel power	kW	Technical
Starboard propulsion power	kW	Technical
Portside propulsion power	kW	Technical
Starboard thruster power	kW	Technical
Portside thruster power	kW	Technical

Once the data has been extracted from the Valmet DNA, it is uploaded to an on-line database, hosted by E-ferry associate partner, Marnav, at ellendata-marnav1.firebaseapp.com. See Figure 10 below.

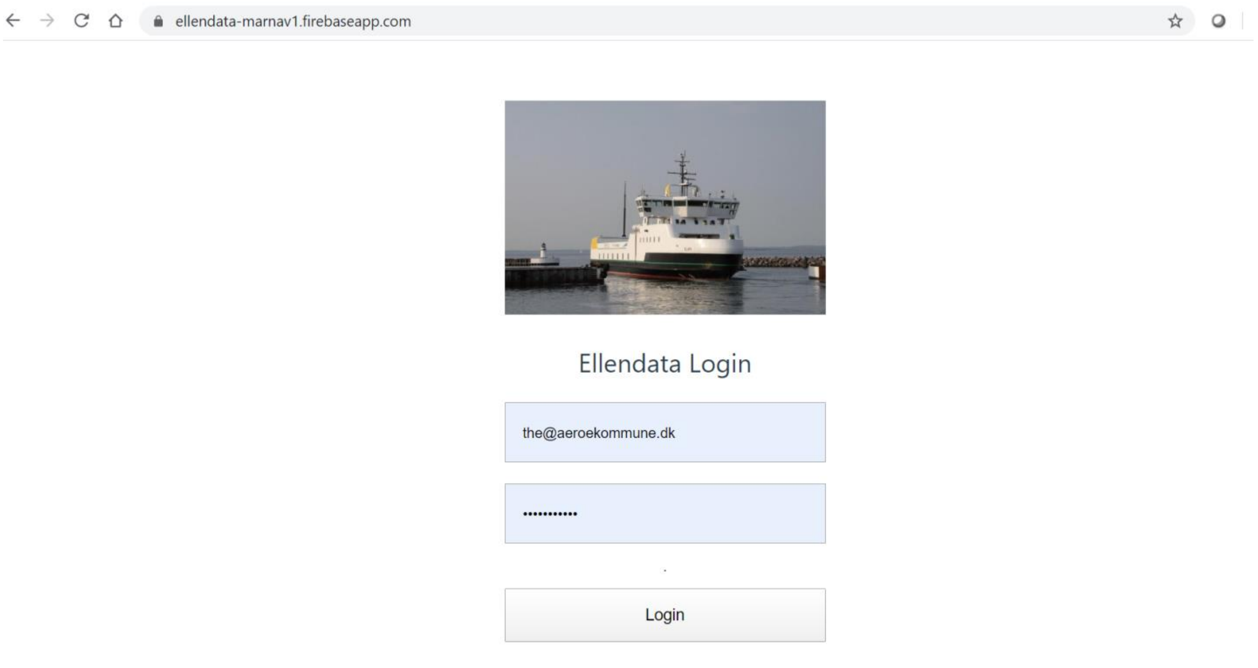


Figure 10: The password protected entrance site to the E-ferry database

The database is password protected and allows for different types of users to get different types of access to the data. The on-line database allows users to specify dates, time intervals (within limits) and parameters that they want to investigate, in three easy steps, as illustrated in Figure 11.

Step 1. Select Dates

Select a single day:
Select/deselect an individual day by clicking the date in the calendar

Select a week:
Select/deselect an entire week by clicking the week number

Select same days in a month
Select/deselect same days (e.g. all Mondays) by clicking on the days name in the top row of the calendar

Select all days in a month
Select/deselect all available days in the month by clicking the headder of the month (e.g. August 2019)

Color coding
No data available
Day selected

August 2019

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
31				1	2	3	4
32	5	6	7	8	9	10	11
33	12	13	14	15	16	17	18
34	19	20	21	22	23	24	25
35	26	27	28	29	30	31	

September 2019

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
35							1
36	2	3	4	5	6	7	8
37	9	10	11	12	13	14	15
38	16	17	18	19	20	21	22
39	23	24	25	26	27	28	29
40	30						

October 2019

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
40		1	2	3	4	5	6
41	7	8	9	10	11	12	13
42	14	15	16	17	18	19	20
43	21	22	23	24	25	26	27
44	28	29	30	31			

November 2019

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
44					1	2	3
45	4	5	6	7	8	9	10
46	11	12	13	14	15	16	17
47	18	19	20	21	22	23	24
48	25	26	27	28	29	30	

Step 2. Select Data

Select data items
The time is always selected by default. Select at least one more item from the shown list.

Select individual items
Select/deselect individual items by clicking the checkbox

Select all items in a group
Select/deselect all available items in a group (e.g. Battery/Power Data) by clicking the group name

Ship/Nautical Data

- COG
- HEADING
- LATITUDE
- LONGITUDE
- LONGITUDINAL SPEED
- RATE OF TURN
- SOG
- SOUNDER DEPTH
- TRANSVERSE SPEED

Wind Data

- WIND DIRECTION
- WIND SPEED
- SB PMS AVAILABLE ENERGY

Power Management Modes

- ACTIVE MODE SAILING
- ACTIVE MODE CHARGING
- ACTIVE MODE MANUAL
- ACTIVE MODE MAINTENANCE

Battery/Power Data

- PS PMS AVAILABLE ENERGY
- DEPTH MEASUREMENT AFT
- SB PMS AVAILABLE POWER
- AC SB HOTEL POWER
- SB BAT 1 SOC
- SB PMS AVAILABLE ENERGY
- SB PROP DR2 POWER
- THRUST1 DR TOTAL POWER SB
- SB PROP DR ROTATION SPEED
- SB PROP DR TORQUE
- DEPTH MEASUREMENT FORE
- PS PMS AVAILABLE POWER
- AC PS HOTEL POWER
- PS BAT 1 SOC
- PS PMS AVAILABLE ENERGY
- PS PROP DR2 POWER
- THRUST1 DR TOTAL POWER PS
- PS PROP DR ROTATION SPEED
- PS PROP DR TORQUE

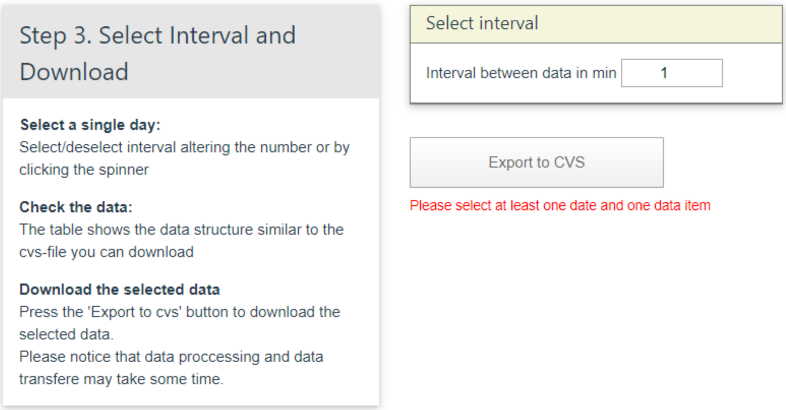
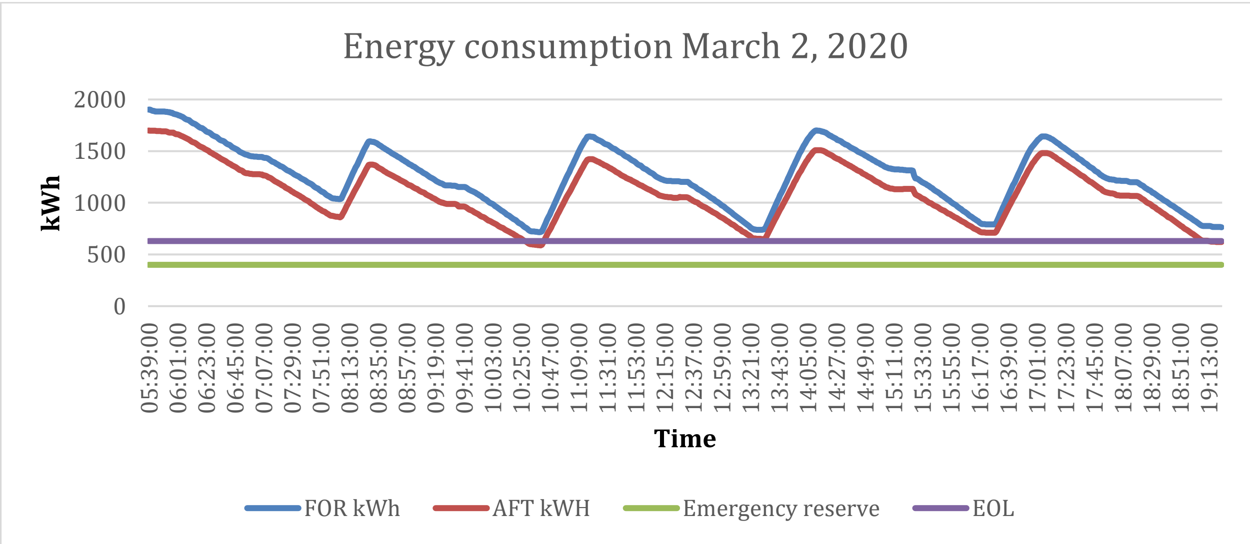


***Figure 11*: Step 1-3 for selecting data in the E-ferry database**

The data extraction is designed, and the parameters chosen, so that it is possible to monitor the vessels overall behaviour as well as to create profiles of e.g. a general route/trip in terms of energy consumption, general efficiency, charging behaviour and so on. In addition, the data extraction allows (on its own or in combination with other data sets, see below) to investigate in more detail any possible correlations between e.g. vessel speed and draught on the one hand, and energy consumption and efficiency on the other hand. Figure 12, for instance, illustrates the operation profile(s) of two days in March 2020, with respect to energy, used and charged over the day. Figure 13 compares the charging pattern of each port stay during March 11, 2020, as depending on State-of-Charge of the two battery rooms and the time used for charging.



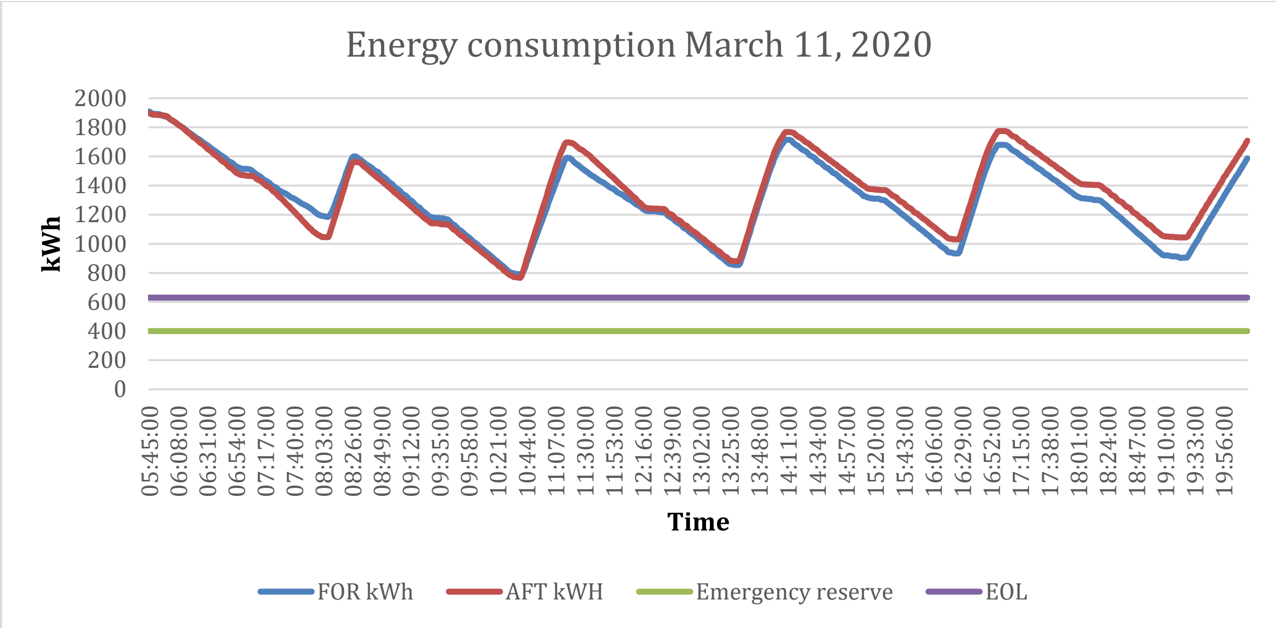
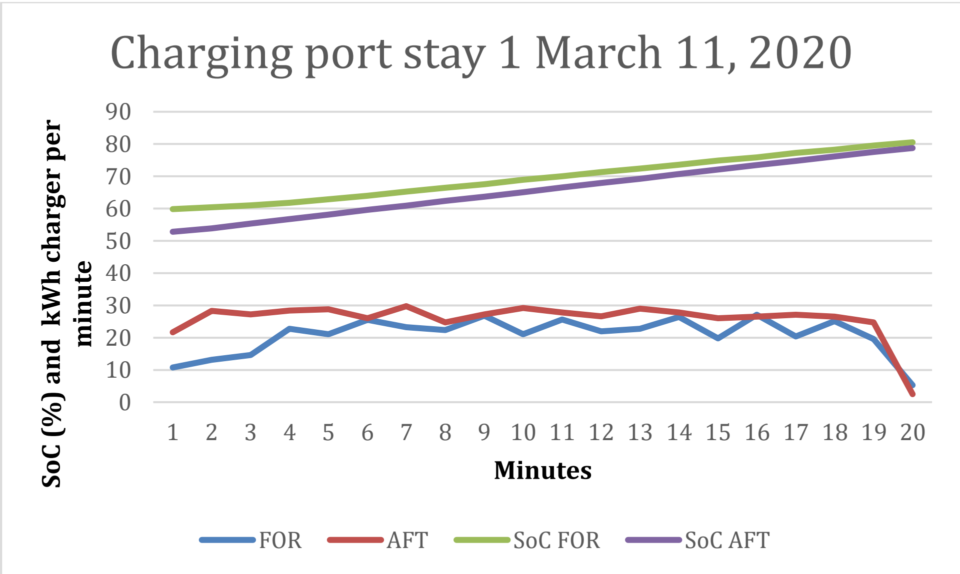
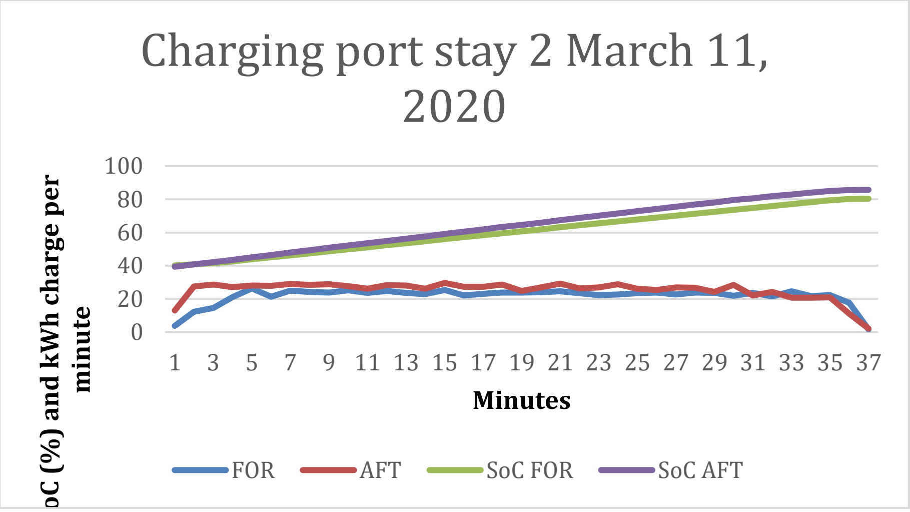
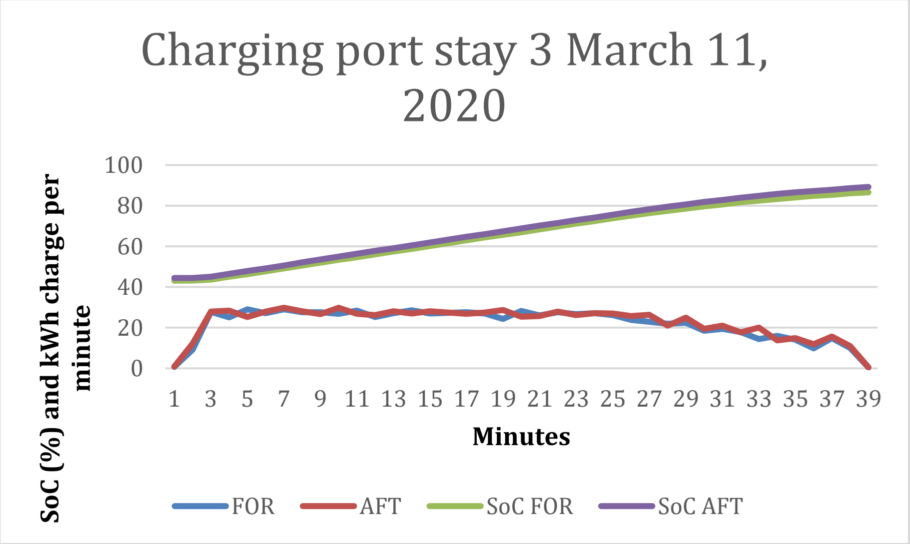


***Figure 12*: Energy consumption patterns for March 2 and 11, 2020**







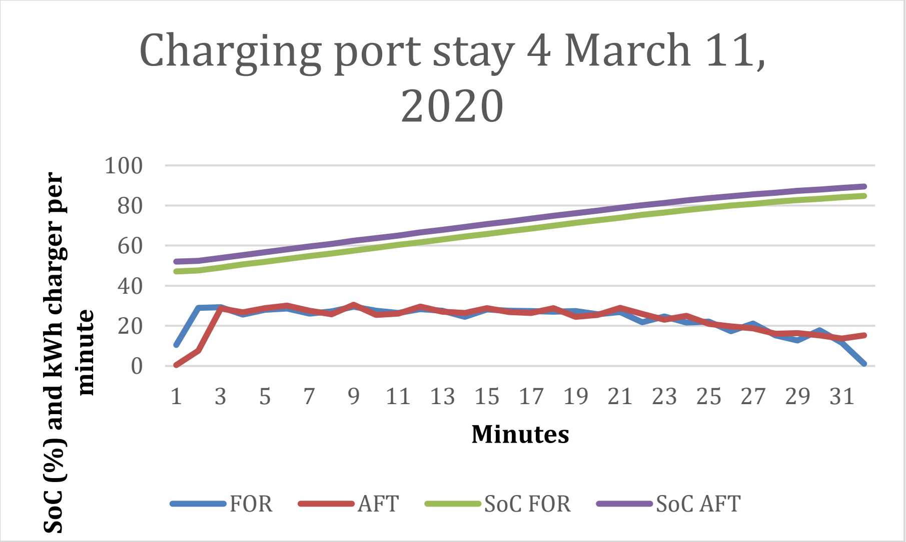


***Figure 13*: Charging pattern of port stays March 11, 2020**

Similar data for e.g. propulsion and thruster consumption of energy during a trip can also be extracted from the database, as illustrated in Figure 14, below, for the first trip from Søby to Fynshav and back, on the 2nd of March, 2020.

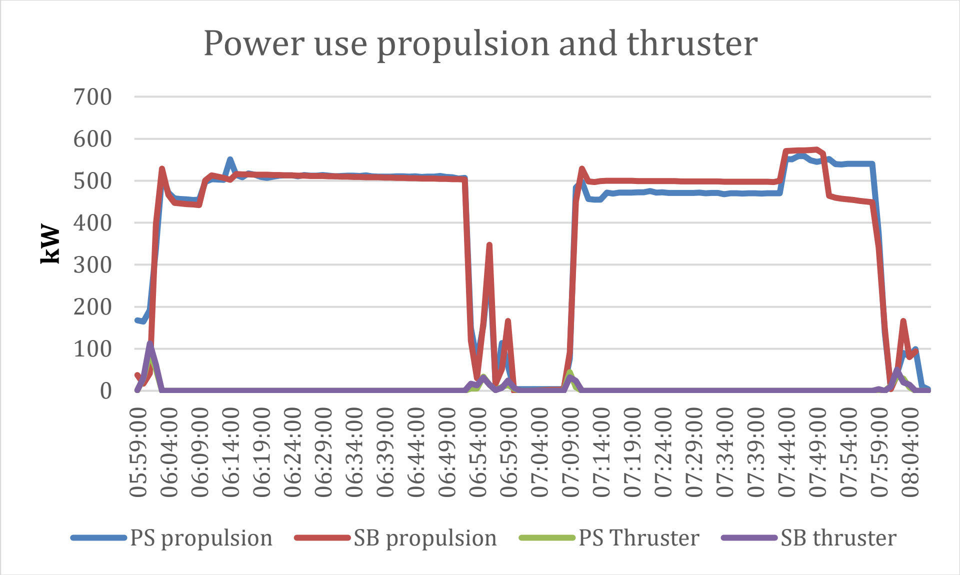


***Figure 14*: Power use, propulsion and thruster, trip 1 March 2, 2020**

While the information provided in the figures above only illustrates how the E-ferry prototype has performed on one or two technical parameters, on a single trip or over a particular day, the overall purpose of the technical performance data has been to evaluate more generally the E-ferry performance and the possible impacts that various variables may have on the performance. For much of the evaluation, the technical and navigational performance data is thus also combined and/or checked against Load and transport statistics (Section 5.1.2) and Weather and oceanographic data (Section 5.1.3).

5.1.2 Load and transport statistics

Load and transport statistics have been provided directly from the operator of the E-ferry, the Aeroe-ferries. As every other operator, Aeroe-ferries monitors the data relating to the number of passengers, cars and trucks on a daily basis, both for reasons of safety and economy. The numbers are reported to Statistics Denmark, where they are made publicly available (statistikbanken.dk), but only as monthly statistics. For the purpose of evaluating the technical and social performance of the E-ferry, it is necessary to be able to gather information about transportation numbers for each trip, for which reason Aeroe-ferries have supplied these data for the evaluation. Figure 15 illustrates the level of detail available with respect to passenger, car and cargo transportation for each trip sailed by the E-ferry prototype on the route from Søby-Fynshav.

B856 30:11

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Ugedag	Dato	Afgang	Overfa	PAX tot	PAX gåend	Bil Trail	Camp	Bus	Last solo	Last anhæn	Last sætt	L Enh	MC	Cyk	
2	Tor.	15:08	06:20	7 Sø > Fy	72	33	19	0	0	0	1	0	2	0	3	
3	Tor.	15:08	07:45	8 Fy > Sø	78	33	21	1	0	0	0	0	0	0	8	
4	Tor.	15:08	12:55	7 Sø > Fy	68	20	20	0	0	0	0	1	2	1	5	
5	Tor.	15:08	15:20	8 Fy > Sø	0	0	0	0	0	0	0	0	0	0	0	
6	Tor.	15:08	18:10	7 Sø > Fy	72	22	21	1	0	0	0	0	0	0	0	
7	Tor.	15:08	19:30	8 Fy > Sø	56	6	25	1	0	0	0	0	0	0	0	
8	Tor.	15:08	09:10	7 Sø > Fy	0	0	0	0	0	0	0	0	0	0	0	
9	Tor.	15:08	14:20	8 Fy > Sø	57	11	20	1	0	0	1	0	2	2	11	
10	Fre.	16:08	06:20	7 Sø > Fy	50	26	13	1	0	0	0	0	0	0	0	
11	Fre.	16:08	07:45	8 Fy > Sø	48	6	18	0	0	0	0	0	0	2	4	
12	Fre.	16:08	12:55	7 Sø > Fy	93	31	27	2	0	0	0	0	0	2	6	
13	Fre.	16:08	15:20	8 Fy > Sø	0	0	0	0	0	0	0	0	0	0	0	
14	Fre.	16:08	18:10	7 Sø > Fy	72	18	20	0	0	0	0	0	0	0	0	
15	Fre.	16:08	19:30	8 Fy > Sø	71	13	28	0	0	0	0	0	0	2	0	
16	Fre.	16:08	20:20	8 Fy > Sø	0	0	0	0	0	0	0	0	0	0	0	
17	Fre.	16:08	14:20	8 Fy > Sø	93	16	27	0	0	0	0	0	0	2	8	
18	Lør.	17:08	06:20	7 Sø > Fy	52	0	18	1	0	0	0	0	0	0	0	
19	Lør.	17:08	07:45	8 Fy > Sø	98	0	21	0	1	0	0	0	0	0	0	
20	Lør.	17:08	12:55	7 Sø > Fy	115	0	25	0	0	0	0	0	0	0	0	

***Figure 15*: Example of the transport statistics for the E-ferry**

The E-ferry evaluation is not intended as a per capita evaluation, e.g. of what the real cost per passenger is, as the E-ferry operator Aeroe-ferries is (as many other ferry operators in Denmark) a public service provider, rather than a commercial business. Thus, details of the number of cars and passengers per trip are in principle irrelevant for the overall evaluation(s), but the transport statistics constitute a good secondary source of data and information, which, when compared to other data sets can serve to relativize, compare and check information gathered in other ways. For instance, as evident from Table 4, on the technical data parameters logged in the Valmet DNA, information about load/cargo should be available through the measurements of ships draught fore and aft. These measurements consist of automated draught measurements, from ship sensors, and can only indirectly provide knowledge about the ferry's load per trip: In port, the onshore ramps will weigh down on the vessel's front (in Søby) or aft (in Fynshav) part, thus changing the natural draught readings when compared to a free-floating vessel in equilibrium. At sea on the other hand, the free-floating ferry will not be lying still, thus squat, waves and other hydrodynamic effect will change the trim and draughts of the ferry, this making stability calculations inaccurate as they are based on static hydro statistical data rather than dynamic. The automated draught measurements will, however, show trends and changes adequately. The availability of transport statistics from the Aeroe-ferries in this respect provides another correlation check to ensure that the measured trend values are as correct as possible. Finally, the daily statistics from Aeroe-ferries also provide information of number of trips, including cancellations, these can then be compared to the overall operation profile extracted from the technical performance data (Section 5.1.1), as well as to the weather and oceanographic data (Section 5.1.3).

5.1.3 Weather and oceanographic data

As illustrated in Table 4 of section 4.1.1.1, some data that relates to the overall weather conditions for the E-ferry operation are registered directly through the navigational equipment on-board the E-ferry. In addition to this source, however, the E-ferry evaluation also includes weather and oceanographic data that is publically available from the Danish Meteorological Institute (DMI) (at dmi.dk). This data includes not only wind direction and wind speed (also collected directly on-board the E-ferry, see Table 4), but also wave height, sea current and sea levels, all of which could be found to be of relevance for the E-ferry energy consumption, as well as its overall ability to perform e.g. in extreme weather.

Combined with the transport statistics as well as technical performance data, the weather and oceanographic makes it possible to determine whether certain types of weather may impact the energy consumption of the E-ferry (positively or negatively) and also – ideally – the underlying reasons for why such impact may occur. Figure 16, below, for instance, illustrates the energy use on 21 return trips in January, 2020, and the wind speed measured and calculated by the DMI on the same trips. As the figure indicates, there appears to be no direct correlation between strong winds and use of energy, probably because the energy use is calculated for a return journey, where e.g. strong headwinds on the way out – which would be expected to lead to a higher energy consumption than average - will be cancelled out by strong tail winds on the returning leg – which would be expected to lead to a lower energy consumption than average (see Section 0, for more details on the impact of weather conditions, including the impact of wind direction for energy consumption and power to propel).

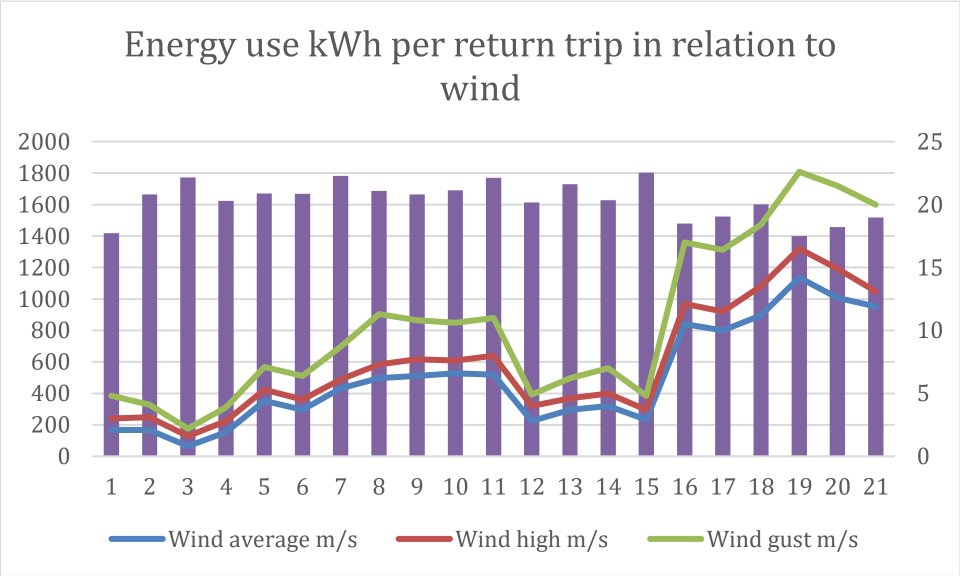


***Figure 16*: Relationship between wind force and energy use in January, 2020**

On-board automated apparent wind direction and speed measurements have been combined with heading and speed over ground (SOG) to calculate true wind speed and direction at the ship's position. These values correlate well with the official wind data from DMI when the ferry is at sea and in open waters. However, when the ferry is at berth and in port on-board measurements will be of little value due to nearby wind obstructions. On the other hand, short time variations caused by gusts and course alterations, as well as sheltering effects due to position can be observed in the automated data sets whereas these are not available in the DMI calculations.

5.1.4 E-ferry prototype performance and evaluation

The main technical goals of the E-ferry was to design, build and demonstrate the validity of a fully electric car- and passenger ferry that could operate in a commercially viable manner on routes of longer distances than 5 nautical miles. To accomplish this main goal, a number of technical design criteria were defined, e.g. in terms of battery capacity, charging effect, design and maximum speed of vessel, weight and loading capacity of vessel and energy efficiency/energy consumption of vessel in operation, crossing and charging time. These design criteria were based on simulations and calculations of how the current E-ferry prototype route from Søby-Fynshav could be operated by a fully electric vessel, sailing up to 7 return trips per day at a decreased crossing time (compared to vessel then operating on the route). The Main Particulars of the E-ferry prototype matches the design criteria determined to be requisite at the beginning of the endeavor - with only very few and very small deviations. The demonstration and evaluation phase has confirmed that the E-ferry prototype is indeed a commercially viable alternative for car- and passenger transport on routes up to 22 nautical miles. The Main particulars of the E-ferry were presented above in Table 1 and again here, in Table 5 below:

***Table 5*: Main Particulars of the E-ferry prototype**

Principal dimensions	
Length, oa	59,4 m.
Length, bp	57 m.
Breadth, moulded	12,8 m.
Depth, moulded	3,70 m.
Gross tonnage	996 t.
Displacement	933 t.
Design, draught	2,5 m.
Design, deadweight	187 t.
Lightweight	746 t.
Deck space	458 m^2
Deck capacity	1,75 t/m^2
Service speed	13,5 kn.
Max speed	14,2 kn.
Capacity and crew	
Lane length vehicle deck	145 m.
Number of cars	31
Number of trucks/trailers	5
Number of passengers	147/196

Number of crew	3/4
Power and propulsion	
Main engines	2x700 kW
Thruster engines	2x250 kW
Nominal battery capacity	4.3 MWh
Charging effect	4 MW
Classification and approvals	
Flag	Denmark
Approval basis	DMA Notice D, RO Directive 2009/15EC, RO regulation (EC) 391/2009, SOLAS Chapter II-2, IMO MSC.1/Circ. 1455
Classification society	DNV GL
Notations	1A1 Car ferry B, Battery(Power), E0, Ice©, PWDK R3

The main deviation from the technical goals is the unsuccessful exploration of implementing composite light-weight solutions onboard vessels of the E-ferry type. In terms of energy consumption and efficiency, weight is of great import to vessels, especially perhaps in electric vessels where the presence of big and heavy battery packs can contribute negatively to the overall energy efficiency and consumption of energy, if the batteries' additional weight is not compensated for with alternative measures, such as for instance the use of light-weight materials such as composite.

If the energy consumption of an electric vessel is too high, e.g. if the E-ferry would consume more energy on a return trip than expected in the design criteria, then measures would have to be taken to mitigate this problem, such measures including e.g. a bigger battery pack (which would then increase the weight again), increased operating time for sea crossings (reducing the speed can reduce the overall energy consumption per mile travelled), a higher charging effect, longer charging breaks, or shorter route travelled between charging. Had it been necessary to implement any of these mitigating measures, the E-ferry could, in all likelihood, not have been demonstrated successfully as a commercially viable alternative to conventional vessels, at least not on the current route of 22 nautical miles. It was, however, a calculated risk to attempt to get approval of composite materials for use on board the E-ferry, also given that the fully electric drive train and batteries in themselves constitute a major deviation from existing approval and classification rules. Risk mitigating measures had consequently been applied from the beginning, in an attempt to reduce both the weight and the energy consumption of the E-ferry in other ways.

Weight mitigating measures thus include: (a) the use of electrical actuators for e.g. bow visor and winches (in lieu of hydraulic systems), (b) the use of aluminium for various parts of the E-ferry (mainly bridge and spoiler), as well as (c) the overall design of the drive train and DC-charging system, with small and light propulsion engines on board and heavy AC/DC transformers on shore. The result of all these measures are that the E-ferry has a light-weight of 746 tons, which is a deviation of around 5% compared to the original design criteria, this despite the lack of composite light weight solutions on board and an increase in the overall weight of the battery- and electric system. According to E-ferry partner NAVAL, a deviation or increase of 5% in weight is in fact well within the standard deviation of 3-9% for conventional vessels of similar size and type as the E-ferry prototype. This when comparing projected versus realized weight for 6 diesel-driven ferries built over the last 15 years for similar operation areas as the E-ferry.

Moreover, as will be seen in the below analysis and discussions, it appears that even this slight increase in weight has not had any noticeable effect on the energy consumption for the E-ferry prototype, perhaps because the hull design has been designed extremely energy efficient, so that lesser resistance in the water compensates for the slightly extra weight.

As the E-ferry Main Particulars thus overall match the design criteria, the more detailed technical evaluation below will focus on the various technical adjustments that were done during the demonstration period to optimize operation and meet as far as possible the technical goals. To evaluate across different types of operation profiles, we have, as noted above in Section 3.2, separated the demonstration period into seven different phases, as follows, with the main adjustments and optimizations being implemented in the 5th period, about 1/3 of time into the overall demonstration period:

***Table 6*: Operation profiles for E-ferry prototype in evaluation period**

Period No	Period	Type of operation	Number of trips per day
1. Training	July 3-August 15, 2019	Training for crew and operator approval	0-3
2. Test operation	August 15-September 8, 2019	Ordinary operation	3-4
3. No operation	September 8-September 15, 2019	No operation due to technical problems	0
4. Test operation	September 15-November 11, 2019	Ordinary operation	3-4

5. No operation	November 11- November 29, 2019	No operation due to optimization work	0
6. Optimized operation	November 30, 2019 – February 29, 2020	Ordinary operation	4
7. Increased operation	March 1 – May 31	Ordinary operation	5-6

For the following technical evaluation, period 3 and 5 have (largely) been excluded, as they involve little or no actual operation with the E-ferry prototype, and hence very little operational data of interest/relevance. The same applies to period 1, which was dedicated to the operator Aeroe-ferries crew training. Though this, of course, included regular operation of the E-ferry prototype, most was dedicated to specific training purposes and did not as such involve sailing from harbour to harbour on the E-ferry prototype route. As a result, the E-ferry cannot for this period (as for periods 3 and 5) be directly assessed for its commercial viability and/or the respect to which its main particulars meet the design criteria as well as the operational needs. For the remainder of the technical evaluation, we thus mainly provide, analyse and compare data from periods 2, 4, 6 and 7. These four periods are furthermore for much (but not all) of the evaluation combined into two larger periods of demonstration.

During period 2 and 4, the E-ferry performance was primarily in the testing phase, though also at the same time in basic operation. During this period, a number of technical problems were encountered and solved, while technical matters that could benefit from some optimization were also identified. During period 5, a number of changes – or adjustments - were thus made to the overall E-ferry system, including increasing the existing battery capacity by replacing some battery modules with new ones, improving the overall software to ensure a better use of the capacity and to reduce the number of warnings and alarms coming from the Integrated Automation System. Moreover, optimization of the E-ferry prototype's manoeuvrability was implemented, by swopping the two propellers.

The two larger periods i.e. before and after the optimization of period 5 can also be characterized as different with respect to crew expertise and routine in operating a fully electric vessel: During the first period and up until at least the period 5 where adjustments were made, crew was lacking the tangible routines of operating the vessel, e.g. in terms of manoeuvring, power load, organizing the loading and off-loading, charging and so on, just as they were somewhat encumbered by having to test a prototype that was not optimized, while at the same time servicing their passengers and meeting an operation schedule. During the latter part of the demonstration period, i.e. after period 5, most crew had by contrast gained a lot of expertise and routine in their work onboard the E-ferry prototype and was moreover operating a vessel with only periodical and mostly insignificant glitches in the technology. As the following evaluation of basic performance parameters will illustrate, the adjustments, optimizations and increase in routine gained over the whole of the demonstration period had a significant impact on the overall technical reliability and overall efficiency of the E-ferry prototype.

5.1.5 E-ferry operation profile

To demonstrate the E-ferry as a commercially viable alternative to conventional diesel-driven vessels, the E-ferry project partners specified that the E-ferry should be able to operate on the route from Søby-Fynshav with up to 7 return trips on any given day, within a time period between 6:00 and 22:30. A typical crew shift with the Aeroe-ferries is 14 hours, so the goal was re-specified as a requirement that the E-ferry prototype is able to sail 5 return shift within a single crew shift, which allocates a total of 13 hours and 15 minutes for actual sailing time, for instance from 6:00-19:15. This goal is comparable to the original goal of 7 trips within 16.5 hours, as it makes the same demands e.g. on crossing time, charging time and time allocated for loading and un-loading (cars). Adding one or more trips on any given day is then a decision that the operator can take in relation to transportation needs and demands, e.g. on selected days in high season, rather than being dependent on the technical capabilities of the E-ferry prototype. A further aspect that needs to be taken into consideration in the planning of an operation schedule is that the trips cannot necessarily be distributed equally over the day, as considerations such as connections to other public transport (busses and trains), as well as interaction with other car- and passenger ferries that operate from the same harbours has to be made. For the E-ferry route specifically, this means that the operation schedules, which the E-ferry should be able to meet, is as illustrated in ***Table 7***, where both departure, arrival, sailing and harbour times are specified:

***Table 7*: E-ferry 5 trip operation schedule for the E-ferry route[1]**

Departure Søby	Sailing time	Arrival Fynshav	Harbour time Fynshav	Departure Fynshav	Sailing time	Arrival Søby	Harbour (and charging) time Søby
06:00	60 min	07:00	10 min	7:10	55 min	8:05	25 min
08:30	60 min	09:30	15 min	9:45	55 min	10:40	40 min
11:20	60 min	12:20	15 min	12:35	55 min	13:30	45 min
14:15	60 min	15:15	15 min	15:30	55 min	16:25	40 min
17:05	60 min	18:05	15 min	18:20	55 min	19:15	N/A[2]

The schedule listed in Table 7 above, is also the schedule at which the E-ferry prototype has been demonstrated, during the second half of the last period of demonstration, i.e. period 7. To test the E-ferry capabilities in a commercial context where delays and cancellations is problematic, however, the

[1] Sailing time from Fynshav to Søby is 5 minutes shorter than from Søby-Fynshav due to less maneuvering.
[2] After the last trip, the E-ferry is slow charged over night.

E-ferry prototype was initially tested on a somewhat more relaxed schedule, with few trips, longer sailing time and longer port/charging times, all of which were gradually increased during the demonstration period to meet the final goal of Table 7. *Table 8* below lists the various operation schedules that the E-ferry was tested to, and in which periods of the overall demonstration phase.

Table 8: E-ferry operation schedules over various periods in demonstration and evaluation phase

Number of trips	Sailing time	Port stay/charging time	Period
3	70 minutes	>one hour	2
4	60 minutes	45-80 minutes	2+4+6
5-6	55-60 minutes	25-45 minutes	7

Successful implementation of the goal or operation schedule in Table 7 requires – for a fully electric ferry - that all aspects of the energy balance are taken into account, this including the actual battery capacity, the energy use/consumption per trip, any energy losses, charging effect and the energy or emergency reserve capacity required by the Danish Maritime Authorities and Classification Society DNV GL. *Figure 17* illustrates the energy balance that was calculated to be accomplished for a 7 trip schedule. As noted above, the requirements for a 5 trip schedule in less time are in fact the same, or at least similar enough to be comparable.

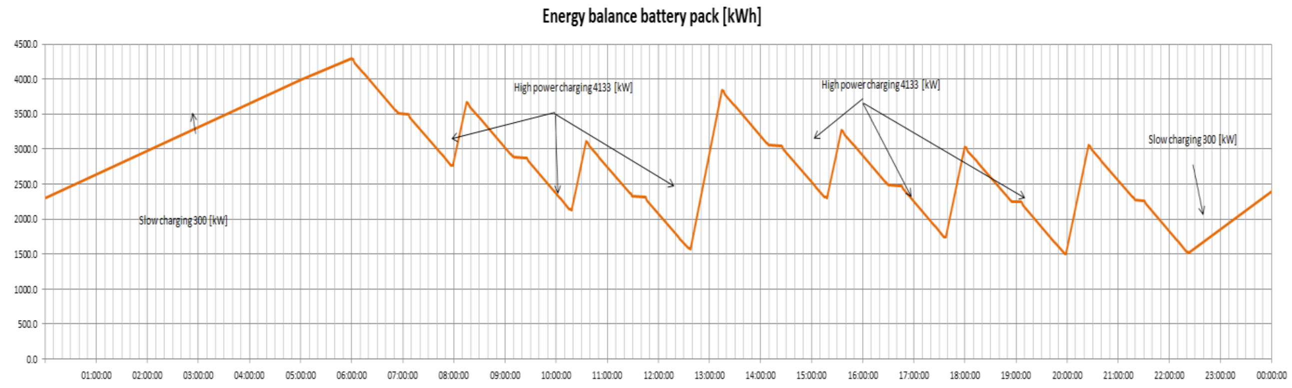


Figure 17: Energy balance – theoretical calculations

Table 9 lists the various parts of the energy balance, the initial expectancies for each of these parts, the risks associated with deviation from expectancies, as well as possible mitigating factors, most of which would entail that the E-ferry is not a commercially viable alternative to diesel-driven vessel. In other words, the indicators and requirements theoretically calculated to be met for the E-ferry prototype to be able to operate the 7 or 5 trips per day within, respectively 16.5 and 13.25 hours.

Table 9: **Factors affecting the overall energy balance for the E-ferry**

Factor	Explanation	Expectancy	Consequence/risk	Mitigation
Actual battery capacity	The actual battery capacity is the capacity available to actually consumer energy from, as opposed to the nominal capacity, which is the capacity to which the batteries can in principle be charged.	3.8-4.1 MWh	If the battery capacity is lower than 3.8 MWh the vessel cannot be charged to this level before setting out on its first trip of the day. Consequently, it will have to charge for longer periods than estimated after each trip, as ‘top up’ strategy cannot be maintained.	Implement longer charging breaks
Energy use/consumption	The actual used capacity from the batteries, during operation, including potential losses from battery system to propeller.	1750 kWh	If the energy use/consumption is higher than 1700 kWh per trip, then too much of the overall capacity will be used on first and second trip and the batteries will have a lower state-of-charge than predicted, with longer charging breaks required.	Increase crossing time (lower speed equals less energy use) and/or implement longer charging breaks
Energy loss from charging to battery	The loss associated with transforming electricity from AC to DC and sending it through inverters, cables and other systems to the batteries.	0,95/ 5%	If loss from charging to battery is higher, energy costs will not only increase, but the charging effect also impacted, with resulting less	Increase length of charging time, or attempt to optimize the charging e.g. on shore side, for less loss.

			energy charged to batteries.	
Energy loss from battery to propeller	The loss associated with sending electricity in DC from batteries through DC/DC converters, cables and DC/AC inverters to the AC engines.	0,92/ 8%	If loss from batteries to propeller is higher than 10%, then overall consumption per knot will increase.	Increase crossing time to lower energy consumption, or attempt to optimize the process of sending energy from battery to propeller.
Emergency reserve	The reserve maintained at all times on each battery system, for emergency purposes in lieu of a back-up diesel generator. Is calculated based on known consumption from various consumer onboard the E-ferry.	240 kWh	If too high a reserve is required, the total usable energy from batteries is reduced, leaving less energy for propulsion.	Attempt to reduce consumption from emergency consumers by optimization, or increase the overall battery capacity, otherwise no mitigation possible, as energy reserve is a requirement.
Charging effect	The effect at which the batteries can be supplied with energy from the shore when aiming for a 1C rate.	4 MW	If charging effect is lower than 4MW, charging time is increased to charge the required amount of energy.	Increase length of charging breaks.

Below, we list each of these parts of the energy balance and evaluate how each part meets the requirements and/or expectations, as well as whether and how these have developed across the demonstration period(s).

5.1.6 Battery capacity

Initially, the nominal capacity of the E-ferry battery systems was specified at 4.3 MWh as being necessary to obtain a commercially viable sailing schedule when taking other predicted/expected energy balance factors into account. Consequently, the E-ferry was equipped with a total of 840 battery modules (distributed over a total of 20 strings, 10 in each separate and redundant battery room (AFT and FOR) of each 5.12 kWh/344 Ah, or a total, per battery room, of 2150 kWh nominal energy capacity, or 4.3 MWh in total. During period 5 where the E-ferry was docked for optimization and adjustments the nominal capacity of the E-ferry battery systems was in fact increased to around 4.4 MWh. Nominal capacity, is defined as the total theoretical energy that can be charged/discharged to/from the pack at the reference C-rate (typically 0.2C, complete discharge in 5 hours) assuming the reference energy capacity of the cell stated by the supplier. To accomplish full use of the nominal capacity, cells in a battery module on board the E-ferry needs to be charged up to the full maximum current of 4.2 Volts. On board the E-ferry, maximum charge was (during the optimization in period 5) set at 4.1 Volt, in accordance also with usual practice, as operating Li ion battery cells at their maximum voltage shortens their operational lives. For the E-ferry battery prototype, this means that the highest available capacity, or 100% State-of-Charge in reality equals 200kWh per string, rather than 215 kWh, so that the total capacity that can be obtained and used onboard the E-ferry is around 4 MWh rather than the nominal capacity of 4.3-4.4 MWh.

Moreover, the energy available that is provided as information for the crew via the Power Management System on the bridge (see Figure *18*) is a calculated value, based – among other things – on a cyclic counter for estimating the State-of-Health of the batteries. A 90% SoH is thus, for instance, calculated based on number of cycles that the batteries have been exposed to and assumes that the battery in question retains 98% of its initial capacity (of 200kWh).

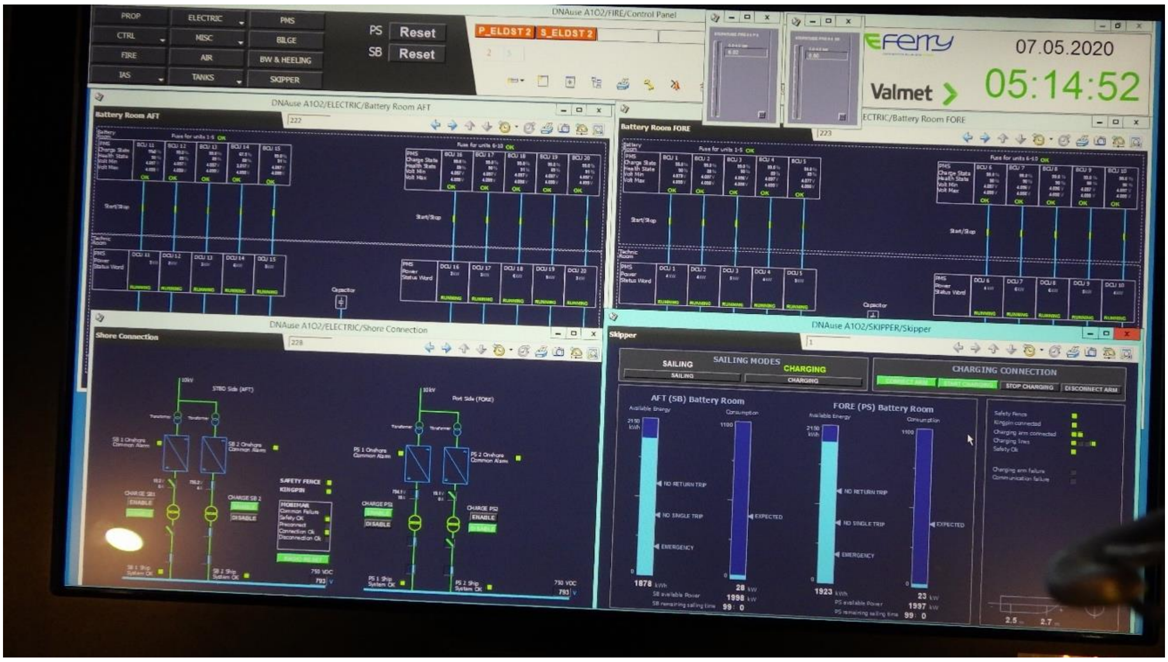


Figure 18: Available calculated battery capacity as shown to crew on bridge as of May 7, 2020, lower right corner.

As the information provided on bridge via the PMS, shown in Figure 18 above illustrates, the maximum calculated available energy based on these measures, is currently (May 2020) around 3.8MWh, this being the achieved capacity that has also been more or less consistently available during the 7th phase of the overall demonstration period. *Figure 19* illustrates the achieved battery capacity during the 7th demonstration period, i.e. the amount of energy available after night charging and before setting out for a day's operation. The 'dips' that occur on march 3, March 4 and April 16 reflect that one string in a battery room has been disconnected, due to either ongoing work on this string or to some alarm fault.

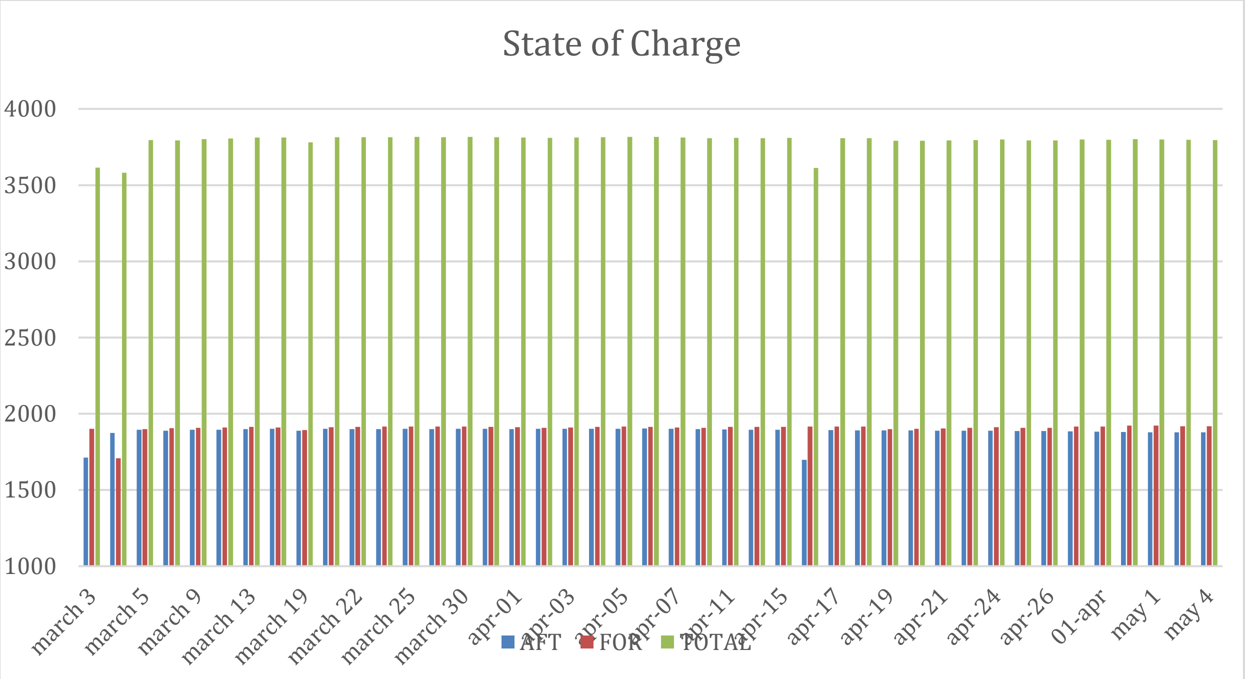


Figure 19: Real available battery capacity on-board the E-ferry prototype during period 7 of the demonstration period

Figure *20* below provides an overview of the overall State-of-Charge and the available energy onboard the E-ferry during this period leading up to the docking in period 5. Data on available kWh have been extracted for every 7 days during that period, with the value extracted being the highest achieved on the day. While the total sum of available energy is not directly comparable to that illustrated in *Figure 19* above, due to subsequent adjustments to software and algorithms, including a new limit of 4.1 V set for the maximum current, it should still be possible to determine that the total energy available during this period is only around 3.5 MWh, moreover, the available energy is not evenly distributed between the two otherwise redundant battery rooms, where in particular the Starboard/AFT room has less energy available than necessary. Specifically, as is also available from *Figure 20*, whereas the PS/FOR battery room reached as much as 1900 kWh stored energy over the period, the SB/AFT battery room rarely got above 1600 kWh.

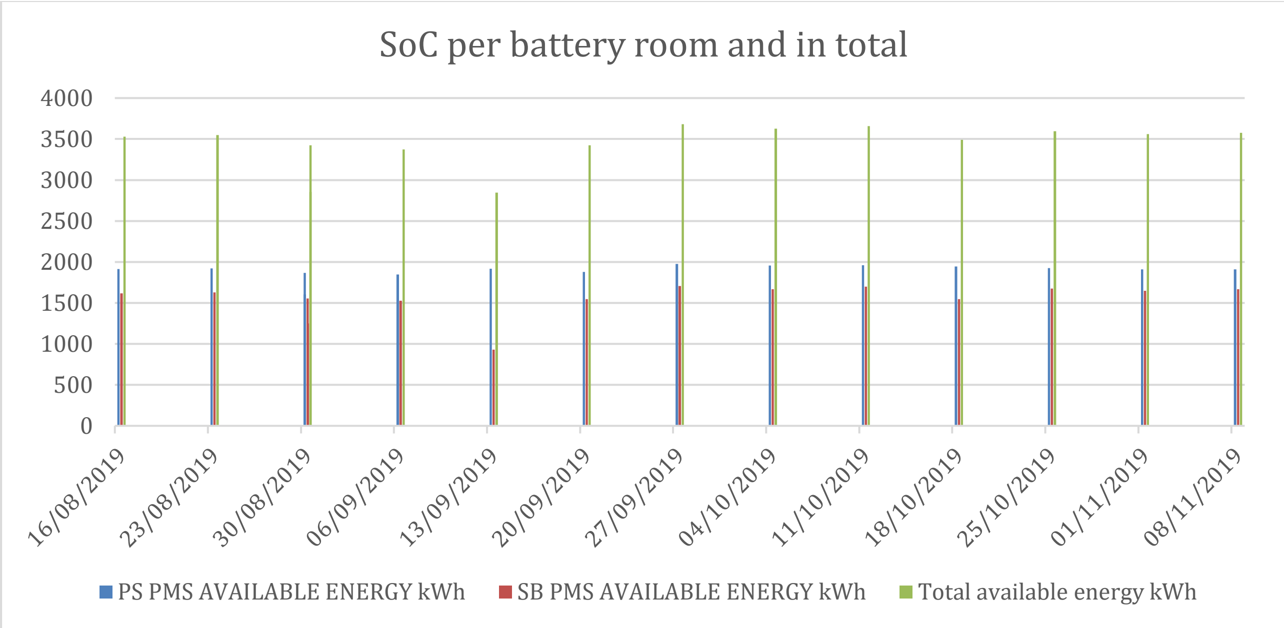


Figure 20: Available energy onboard E-ferry during period 1-4 of the demonstration phase, before adjustments and optimizations

The fact that the uneven distribution of energy available between the two battery rooms can in principle be a problem for operational safety and certainly for the operational life-time of the battery is perhaps evident from Figure *21* and Figure *22* below, each illustrating the overall energy balance during the first parts of the demonstration period, i.e. periods 2 and 4 (Test operation). *Figure 21* illustrates the energy balance of the E-ferry prototype when operating on a 3 trip schedule, *Figure 22* the same when operating on a 4 trip schedule. For both figures, data is extracted on consecutive Fridays, with extreme dips presumably caused either by a glitch in the data collection or by one or more battery strings being disconnected due to ongoing work or alarm fault.

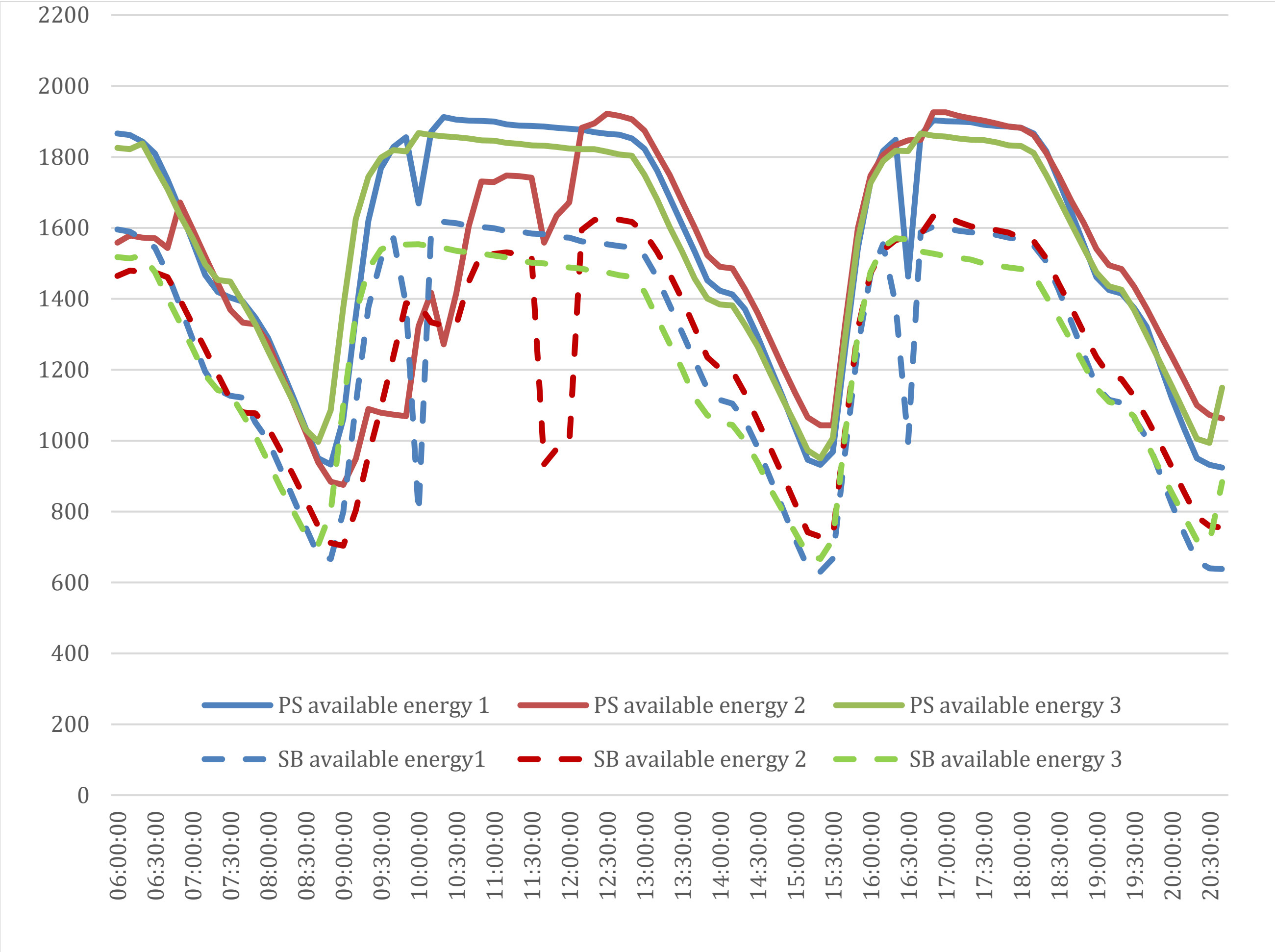


Figure 21: Energy balance for E-ferry prototype with 3.5 MWh energy available and sailing on three return trip schedule

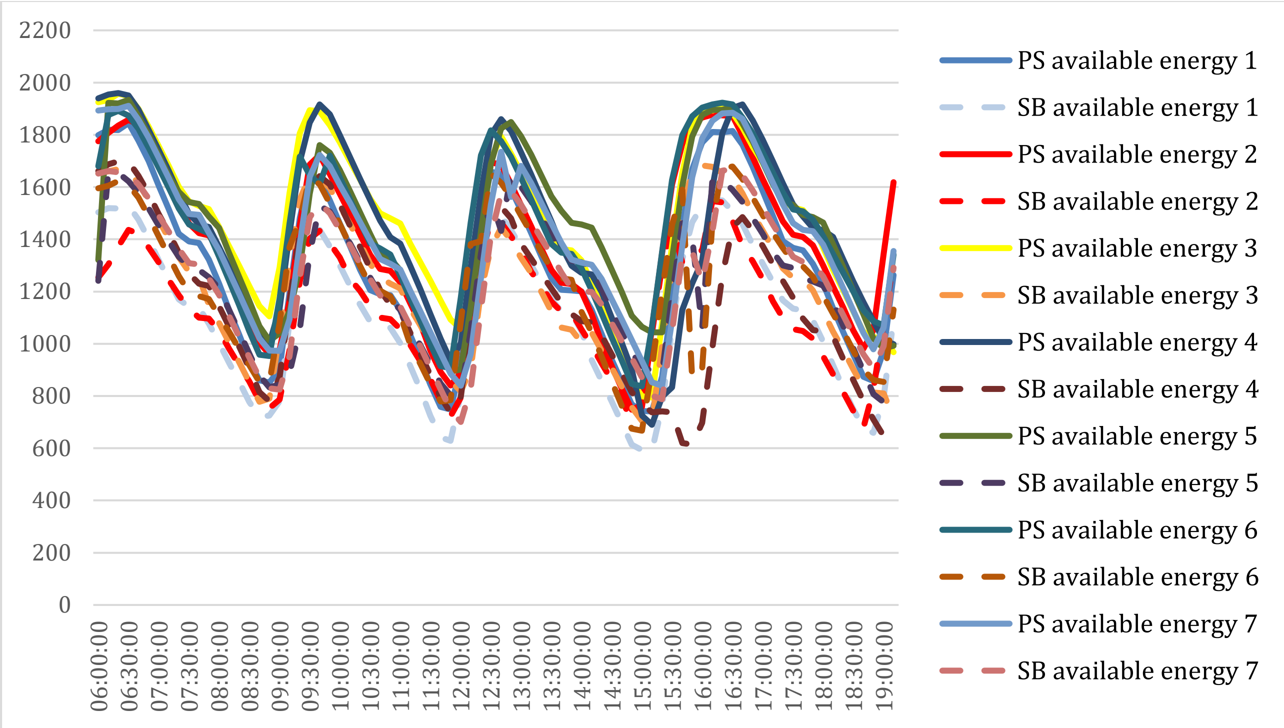


Figure 22: Energy balance for E-ferry prototype with 3.5 MWh energy available and sailing on four return trip schedule

For both energy balances illustrated above, the lower energy capacity available means that even when operating on only a three trips per day schedule, the 30% recommended Depth of Discharge to ensure life-time of the batteries, will be regularly breached at least for the Starboard (Aft) battery room. The 30% DoD recommendation for a nominal capacity of 2150 kWh per battery room is 645 kWh. With a three trips a day schedule, the 30% DoD was breached regularly on the third trip of the day, with four trips a day the level was breached more or less throughout the day, on every trip but the first. It is worth noting here that during this period, crew operated the ship in a manner that used the starboard and forward propulsion engines unevenly, so that less power was drawn from the already weak starboard/AFT side, but even with this mitigating operation profile, the DoD recommendation was nevertheless breached – and on a regular basis. The only way to avoid this would be to extend the charging breaks further to ensure that the starboard/AFT battery room was charged to its full available capacity of 16-1700 kWh after each trip. As this would require charging breaks of over 1 1/2 hours, however, this mean that the concept of the E-ferry prototype would no longer be commercially viable, as the frequency of operation would be severely reduced. Needless to say, the lower battery capacity of 3.5 MWh and in particular the uneven distribution of energy with starboard battery room reaching between 16-1700 kWh also meant that it would be impossible to implement a five trip per day schedule that would be commercially satisfactory, i.e. without charging breaks of 1.5 hours between each trip.

With the work implemented during the docking period 5, however, the E-ferry prototype battery capacity was brought up to 3.8 MWh, as illustrated in Figure 19 above. The energy balance of the E-ferry prototype in relation to the battery capacity was subsequently tested first with 4 trips per day, and then from March 2020 with 5 trips per day. Figure *23* and Figure *24* illustrate the energy balance for these two profiles, here with the 645 kWh DoD recommendation included, to illustrate how the increased available battery capacity allows for the E-ferry to routinely stay above this level, and only breach the DoD recommendation in special circumstances and on an irregular basis.

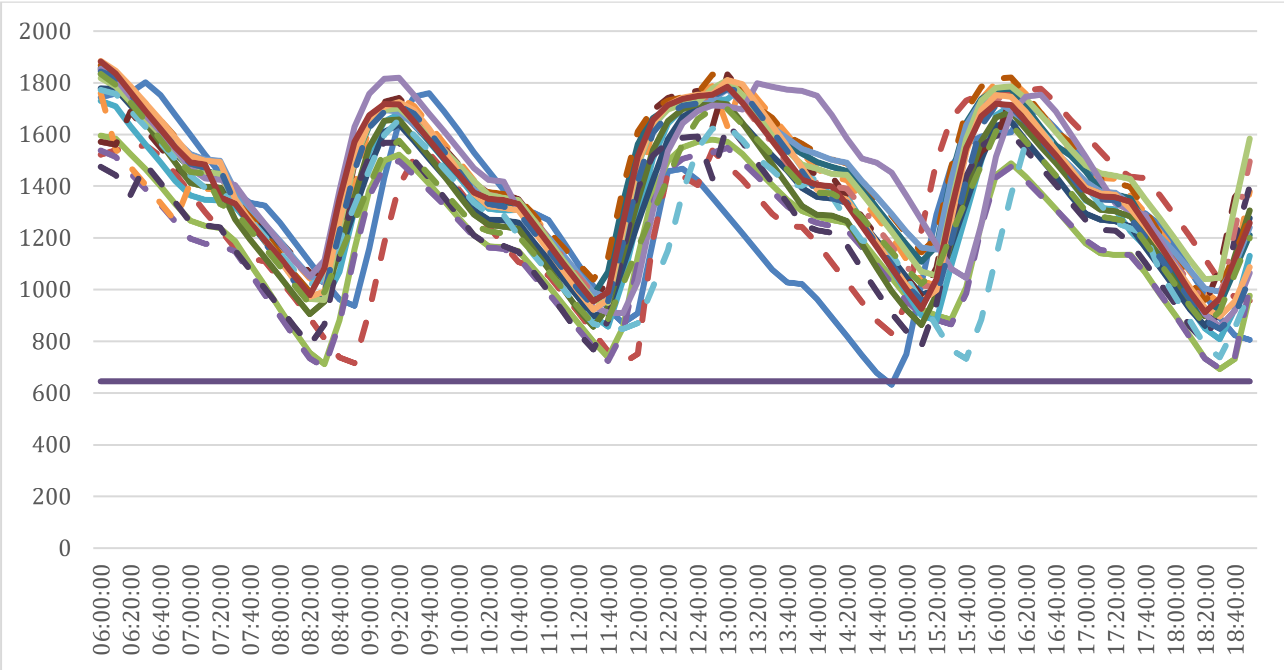


Figure 23: Energy balance for E-ferry prototype with 3.8 MWh energy available and sailing on four return trip schedule

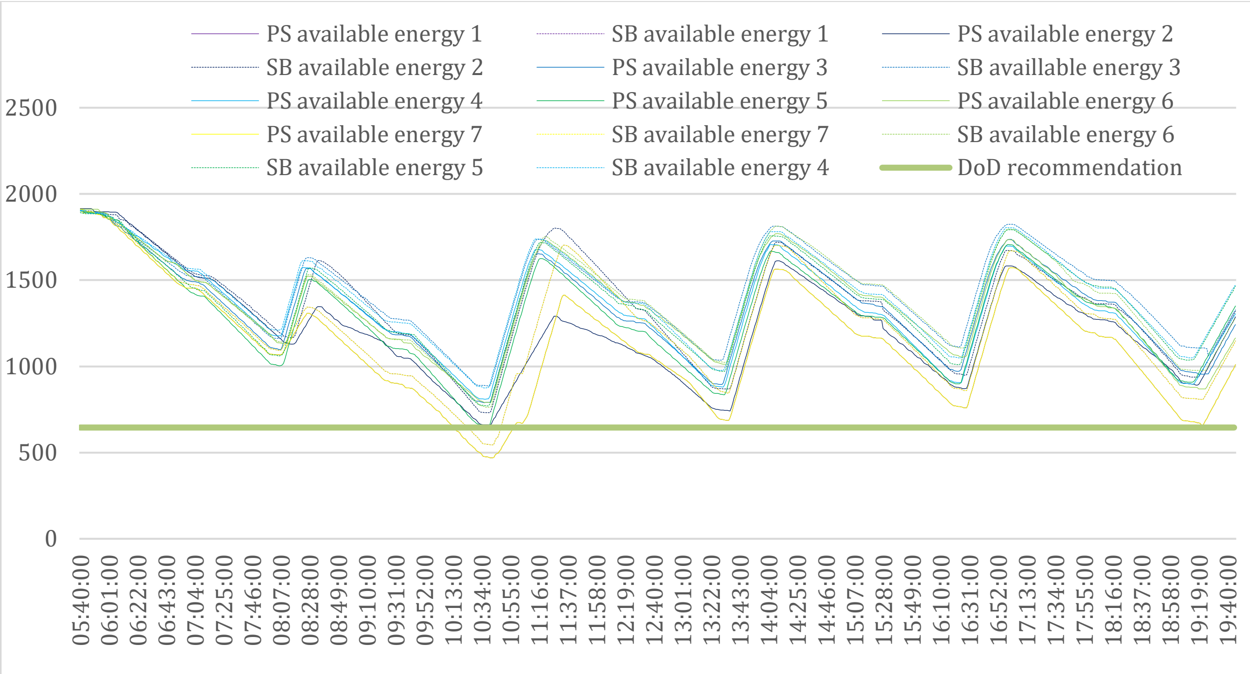


Figure 24: Energy balance for E-ferry prototype with 3.8 MWh energy available and sailing on five return trip schedule

As can be seen from *Figure 23* and *Figure 24* above, the E-ferry energy balance routinely stays above the recommended DoD of 645 kWh (30%) during the last period of the demonstration, where achieved battery capacity was just above 3.8 MWh. Even on the somewhat rougher sailing schedule of period 7, where harbour/charging breaks are as short as 25 minutes, e.g. after the first trip of the day, the DoD recommendation is only breached in special circumstances. Even so, the 3.8 MWh achieved battery capacity is not the final end goal in the E-ferry project, as there are still a few battery strings that are not fully optimized, and on which work is still ongoing. Energy use/consumption

Initial requirement or expectation for the E-ferry prototype energy use or consumption, was, as listed in Table 9 above, a total of maximum 1750kWh per return trip from Søby-Fynshav-Søby, this including energy consumption for other systems than propulsion (i.e. hotel load), as well as the potential loss of energy from battery systems to propellers and switchboards. The requirement/expectation was based on simulated data for the hull design and the route, as well as input about consumers and their needed power. Energy consumption for propulsion is, moreover, as noted above, potentially dependent on the weight and/or load of a vessel, as well as the speed at which the vessel's engines need to run in order to obtain the required crossing speed, independently of, for instance, strong winds against the sailing direction. In other words, there are quite a number of factors that can either lessen or increase theoretically calculated or simulated energy consumption. However, as demonstrated in *Table 10*, below, the average actual energy consumed per trip by the E-ferry prototype has in fact been below the expected/required maximum of 1750 kWh throughout the whole demonstration period.

Table 10: Average energy consumption per trip, separated into different stages of the demonstration period.

Average energy consumption per trip	Period	Number of trips	Scheduled sailing time	Port stay/charging time
1703 kWh	1 (training)	0-3	70 minutes	>one hour
1685 kWh	2	3	70 minutes	>one hour
1707 kWh	2+4	3-4	60 minutes	45-80 minutes
1596 kWh	6	4	60 minutes	45-80 minutes
1566 kWh	7	5	55-60 minutes	25-45 minutes

As should be quite evident from Table 10, not only is the average energy consumption of the E-ferry per trip lower than the maximum specified 1750 kWh, but the energy consumption has also decreased rather significantly over the demonstration period, so that energy consumption per trip is about 8% lower in period 7 than it was in period 1, and 7% lower in the last half of the demonstration period (after optimizations of period 5) than the first half of the demonstration period (before the optimizations of period 5). In theory, as the crossing time for the E-ferry prototype was also decreased over the periods, from initially up to 70 minutes, to the current expected/required 55/60 minutes, it could have been expected that the energy consumption would have increased over the demonstration period, as higher speed would lead to a higher power demand from the engines.

As also illustrated in Table 10 above, this theoretical possibility did not apply, and the reason for the decreased in energy consumption over time should thus presumably be grounded in the combination of 3 factors: Firstly, it is likely that the drive train efficiencies were improved during the optimizations done to the Battery Management System during the docking of period 5. Secondly, the docking in period 5 also included the interchanging of the propellers, which had been identified as leading to better maneuverability, both in simulated operation and during the period of ordinary operation leading up to the docking in period 5. Thirdly – and probably most significantly – the crew operating the E-ferry prototype will have gradually become more and more experienced with the differences between operating a fully electric vessel, e.g. in terms of power demand for propellers, as compared to a conventional diesel-propelled vessel, where reaction time is much slower. And alongside the interchange of the propellers, crew would also gradually have become more accustomed with maneuvering in and out of the two harbors (both of them quite narrow and exposed in terms of wind). As the maneuvering time is included in the overall crossing time, a shortening of the maneuvering time naturally leads to less need to extreme power demands for extra speed during the actual sea crossing, and this can in turn also account for the decrease in energy consumption, especially when taking the other factors into account as well.

The decrease in energy consumption can also be seen when detailing the energy consumption per month, as in *Table 11* below, with Figure 25 illustrating the variation in energy consumption, also across the whole demonstration period, up until mid March.

Table 11: *Trend in energy consumption for each month in the demonstration period.*

Period	Month	Average energy consumption
1+2	August	1711 kWh
2+4	September	1666 kWh
4	October	1719 kWh
4	November	1708 kWh
6	December	1561 kWh
6	January	1603 kWh
6	February	1624 kWh
7	March	1567 kWh

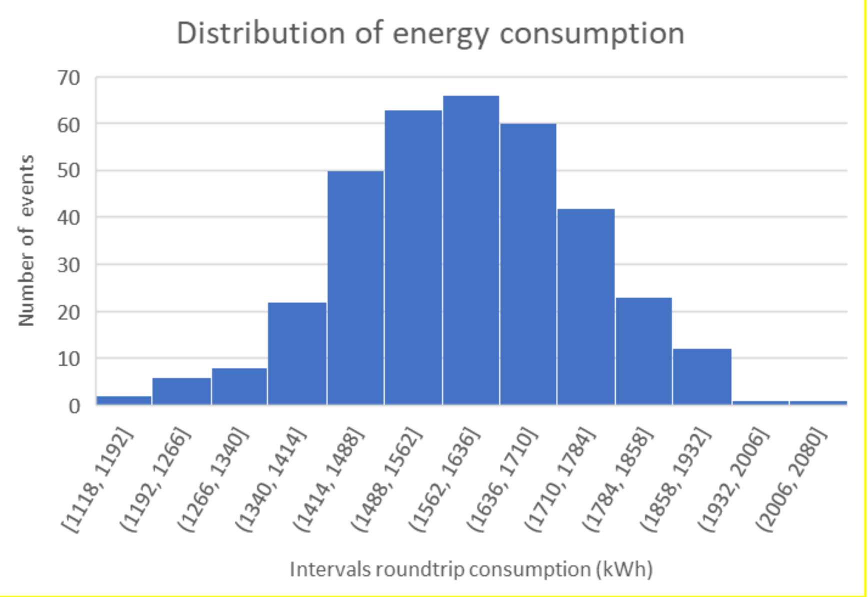


Figure 25: Distribution of energy consumption variation per roundtrip from 15th of August 2019 to 11th of March 2020.

Interestingly, the standard deviation of energy consumption per return trip after the docking of period 5 at 150 kWh, meaning that 95% of all return trips lie within 1300-1900 kWh, is higher than that for the period before the optimization. This again points to the possibility that the optimization implemented during period 5 had a significant and positive impact on the overall performance of the E-ferry prototype. Thus, the higher standard deviation in energy consumption could be interpreted so that the higher energy capacity and better manoeuvring has provided the crew with more flexibility in terms of making on-line adjustments to e.g. speed and power demand in relation to the real-time conditions of the operation. That is, to say, that with a better performing vessel overall, the crew has the possibility of e.g. increasing the speed without being concerned with using too much energy when a delay has occurred for whatever reason.

Another potential reason for the higher deviation in energy consumption average during periods 6 and 7 could be the variation in average energy consumption that can be observed for those periods per month in the detailed view in Table *11* above. Thus, while the table illustrates that there is a general decrease in energy consumption between period 4 and 6/7 respectively, which as discussed above can at least partially be accounted for as grounded in the optimizations implemented during the docking of period 5, both January and February month of 2020 had a somewhat higher average energy consumption per return trip than in December and March, though still significantly lower than the mean average of the periods before the optimization. As January and February were extremely windy in 2020, the somewhat higher average energy consumption during these months could potentially be ascribed to the need for using more power when sailing against the wind or for manoeuvring in more difficult circumstances. The distribution and variation in energy consumption overall, however, does not match the Weibull distribution of wind speeds, which could be expected if the wind speeds were the sole factor for increased energy consumption. This is evident when comparing the Weibull distribution of wind speed variation in Figure 26 below, with the normal variational distribution of energy consumption.

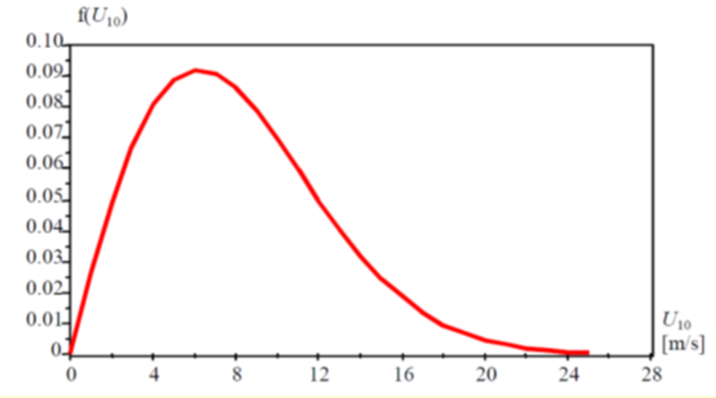


Figure 26 Wind speed variation over one year based on data from Energi- og Miljø-Data EMD.dk

While the standard deviation pattern for variation in energy consumption does not correlate with the standard deviation pattern for wind speed variation, it is evident nevertheless that wind speed at least at certain directions does impact not only the energy consumption, but also the speed of the vessel. This is illustrated in Figure 27 and Figure 28 below, where the first one illustrates the overall relation between speed and power demand from engines for periods 6 and 7 in general, whereas the latter illustrates the same relation during operation at wind speeds above 25 knots.

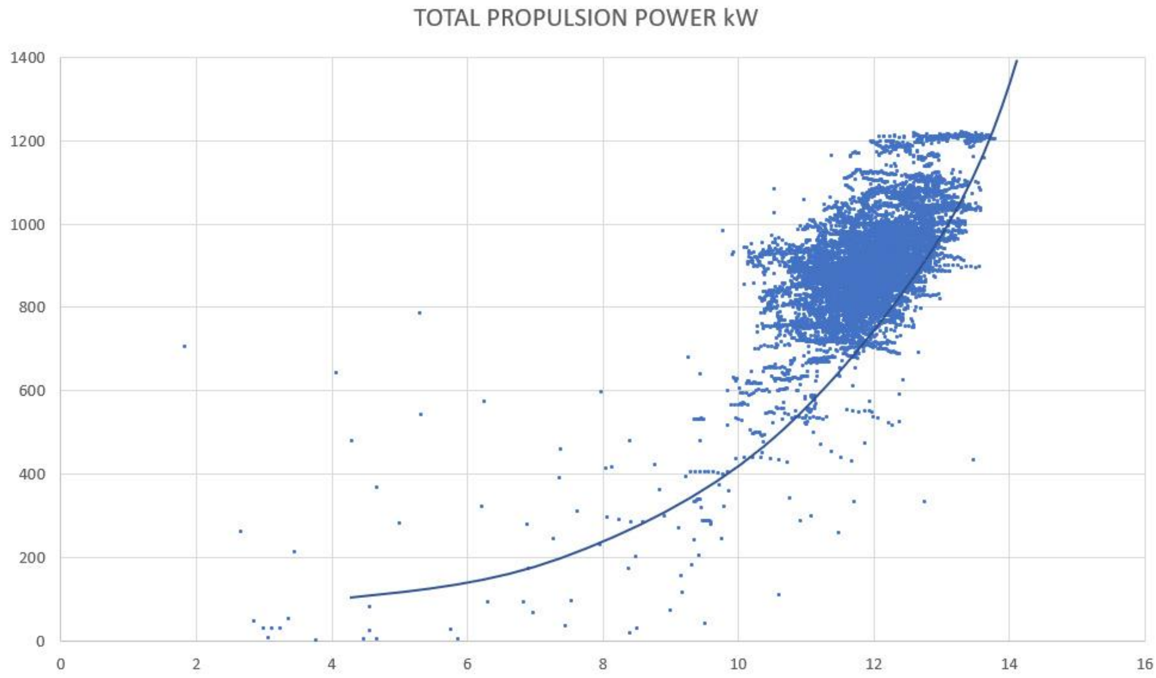


Figure 27 Plot of speed power data during all weather and load conditions. Data from period 6 and 7 of the demonstration period.

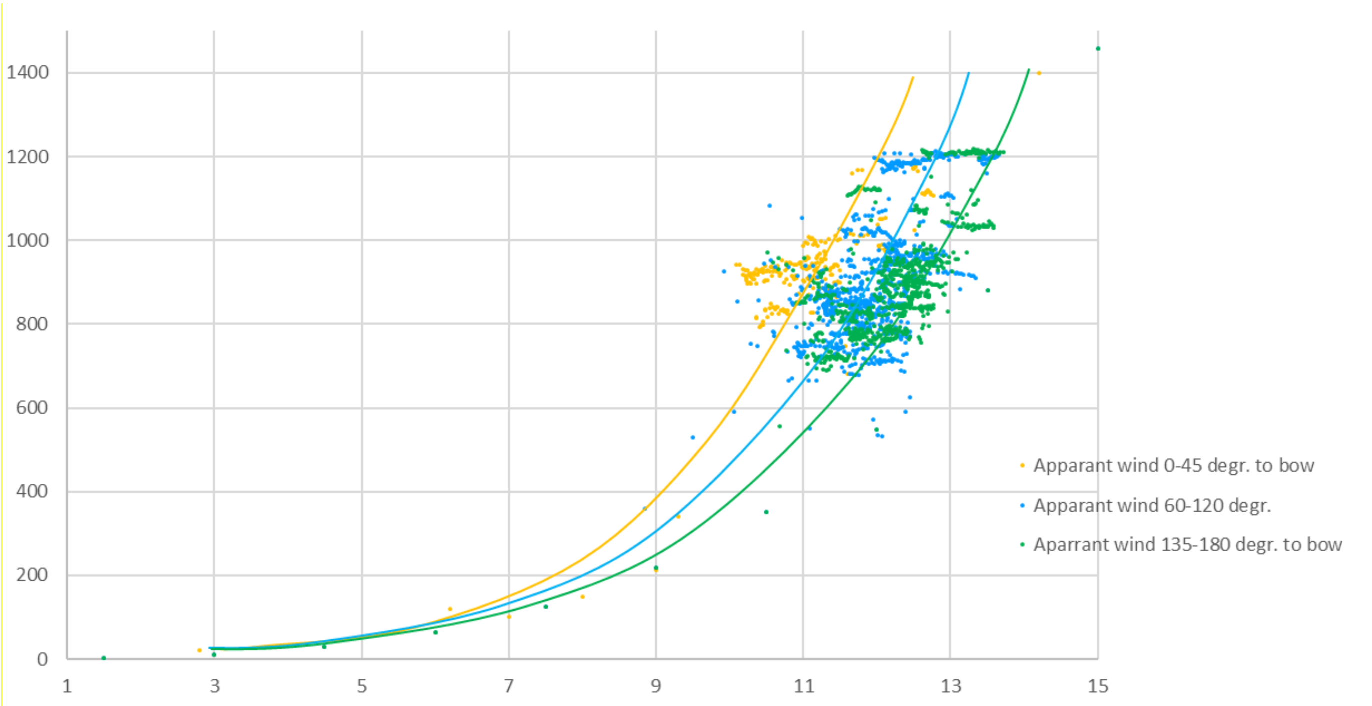


Figure 28 Data plots from wind conditions over 25 knots with water depths below keel above 15 metres. Apparent wind speed measured onboard and relative wind indicated +/- 180° according to the bow/heading.

As illustrated in Figure 27, at ideal conditions of calm water and little wind, the E-ferry prototype can reach a speed of around 14 knots at a power demand of 1400 kW engine power (this being also the highest engine power possible). This relation was also tested an observed at the E-ferry sea-trials and as such constitute the maximum speed of 14.2 knots in the specifications (see Table 1). For operational purposes, however, the E-ferry for most of the time sails at a speed between 12-13 knots, which constitutes and is equal with the required service speed of 13.2 knots for which speeds a power demand of 1000-1200 kW seems the most common. If we compare these data, however, with the curves in Figure 28, we can see that in conditions of heavy wind (above 25 knot wind speed), the speed obtained with the relative power demand differs, depending in particular on the wind direction:

If the wind is between 135-180 degrees to the bow (i.e. from the back and in the sailing direction, see the green line in Figure 30), the maximal speed reached at full power demand of 1400 kW is similar to (or slightly above) the maximum speed, i.e. above 14 knots). If, however, the wind comes from the side (60-120 degrees, see the blue line in Figure 30) the maximal speed reached at full power demand of 1400 kW is just over 13.2 knots, which is lower than the maximal speed obtainable under less windy conditions. Finally, as illustrated by the yellow line in Figure 28, wind directions straight to the bow, meaning that the E-ferry sails directly against the wind (0-45 degrees) decreases the obtainable speed significantly, so that the full power demand of 1400 kW provides a speed of only just over 12 knots.

In terms of energy consumption, this in turn means that as more power is required to cross in the scheduled time, more energy would also be expected to be used on legs in windy conditions, as was for instance the case on many days in January and February 2020. E-ferry crew, however, have the impression that when strong winds come from the bow and reduces speed on one leg of a return trip, this reduction of speed will be offset on the second leg of the trip, where the E-ferry is sailing with the wind instead. This observation is firstly supported by the difference between the yellow and the green line in Figure 28, and by a secondary method of investigation of the energy consumption, illustrated in Figure 29 below, where energy consumption per return trip has been logged manually by crew, with data on wind and cargo being supplied later, from the Weather and oceanographic data and the Load and transport statistics, respectively. As Figure 29 illustrates, conditional formatting has been used to determine any correlations between energy consumption and high wind speeds, as well as between energy consumption and heavy cargo loads (see below for discussion on this correlation).

	A	B	C	D	E	F	L	M	N	O	Q	R	S	Y
1				Consumption (kWh)			Run. Avg. 4		Date and time	Wind avg	Wind gusts		Car	Cargo load
2	Month	Date	Trip	Aft	Forward	Total	trips (kWh)		dd-mm-åååå tt-mm	m/s	m/s		units	ton
108	Februar	12	4	869	923	1792	851,8		12-02-2020 17:00	10,5	20,4		10	25
109	Februar	12	3	538	1034	1572	805,5		12-02-2020 13:00	10,3	18,3		24	90
110	Februar	12	2	729	841	1570	786,8		12-02-2020 10:00	10,9	18,8		14	35
111	Februar	12	1	928	952	1880	767,3		12-02-2020 07:00	11	19,6		13	62,5
112	Februar	11	4	623	799	1422	736,8		11-02-2020 17:00	10,6	18,9		16	60
113	Februar	11	3	623	799	1422	795,5		11-02-2020 13:00	11	17,9		18	135
114	Februar	11	2	593	821	1414	840,0		11-02-2020 10:00	10,4	18,5		16	40
115	Februar	11	1	677	959	1636	900,4		11-02-2020 07:00	9,6	17,9		9	52,5
116	Februar	9	1	921	971	1892	946,0		09-02-2020 10:00	10	16,6		33	82,5
117	Februar	8	2	887	891	1778	882,8		08-02-2020 10:00	5,8	9		19	47,5
118	Februar	8	1	924	973	1897	859,6		08-02-2020 07:00	5,2	9,3		11	27,5
119	Februar	7	4	865	852	1717	835,4		07-02-2020 17:00	3,2	6,7		21	72,5
120	Februar	7	3	804	866	1670	815,4		07-02-2020 13:00	2,7	5,1		35	107,5
121	Februar	7	2	783	810	1593	779,0		07-02-2020 10:00	1	3,4		20	90
122	Februar	7	1	825	878	1703	759,4		07-02-2020 07:00	1,5	3,4		14	115
123	Februar	6	4	777	780	1557	759,4		06-02-2020 17:00	5,7	10		19	59,5
124	Februar	6	3	672	707	1379	778,6		06-02-2020 13:00	6,5	10,7		15	67,5
125	Februar	6	2	677	759	1436	826,9		06-02-2020 10:00	6	10		15	37,5
126	Februar	6	1	825	878	1703	840,6		06-02-2020 07:00	6,1	9,7		13	102,5
127	Februar	5	4	823	888	1711	863,6		05-02-2020 17:00	7,1	11,9		18	45
128	Februar	5	3	881	884	1765	854,0		05-02-2020 13:00	5,1	8,1		13	142,5
129	Februar	5	2	748	798	1546	805,0		05-02-2020 10:00	3,2	7,4		13	32,5
130	Februar	5	1	934	953	1887	795,9		05-02-2020 07:00	4,1	6,8		13	102,5
131	Februar	4	4	794	840	1634	771,0		04-02-2020 17:00	9,3	14,8		11	117,5
132	Februar	4	3	671	702	1373	778,0		04-02-2020 13:00	7,1	12		23	97,5
133	Februar	4	2	731	742	1473	819,5		04-02-2020 10:00	5,7	10,6		6	125
134	Februar	4	1	838	850	1688	830,5		04-02-2020 07:00	6,1	10,7		21	52,5

Figure 29 Sample from the spread sheet method used to analyse for correlations to energy consumption per roundtrip. Shown roundtrips are from the beginning of February where high wind speeds led to cancellation of trips on the 8th and 9th of February.

The conditional formatting and analysis of this cannot be used to conclude that wind speeds affect the energy consumption per return-trip, as both low and high consumption trips can be found at high wind speeds, e.g. on February 11 and 12, just as high and low consumptions trips occur at low wind speeds, e.g. on February 6 and 7. In fact, what the crew has observed in terms of one leg of the trip cancelling out the other leg, seems to apply in quite general terms, as illustrated in Figure 30, Figure 31 and Figure 32, where the speed over ground in relation to the power demand from engine has been plotted for each return trip sailed during the first week of March 2020.

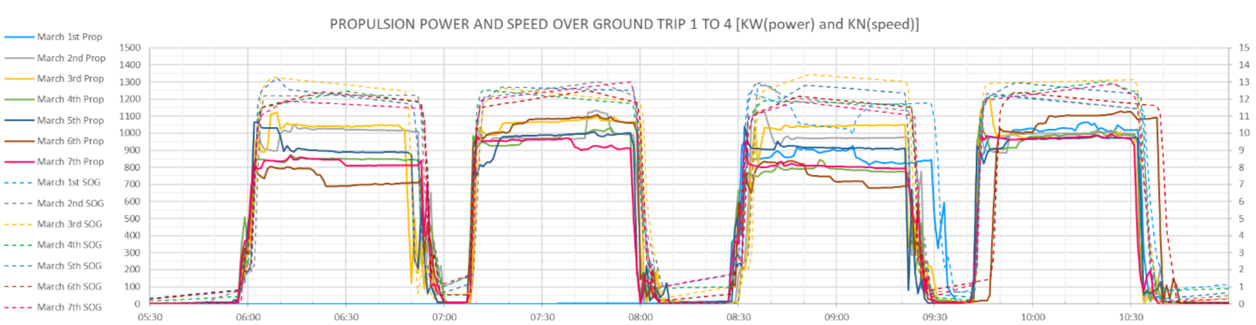


Figure 30 Propulsion Power (left axis) and Speed Over Ground (right axis) for first and second roundtrip first week of March.

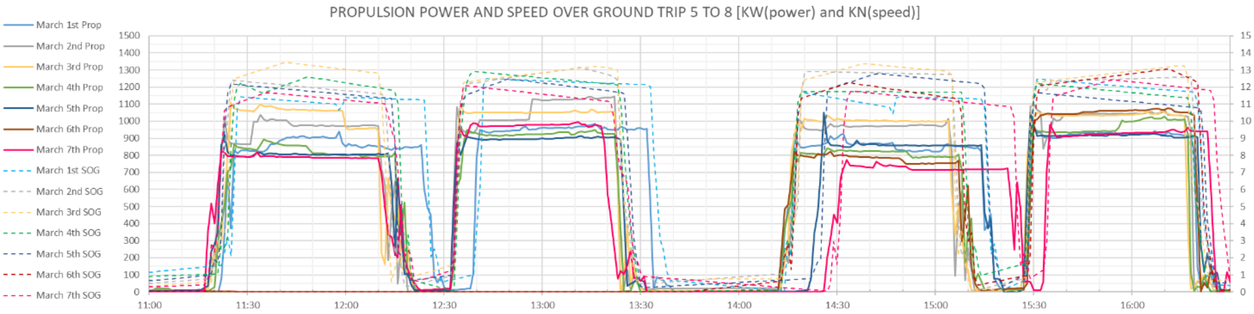


Figure 31 Propulsion Power (left axis) and Speed Over Ground (right axis) for third and fourth roundtrip first week of March.

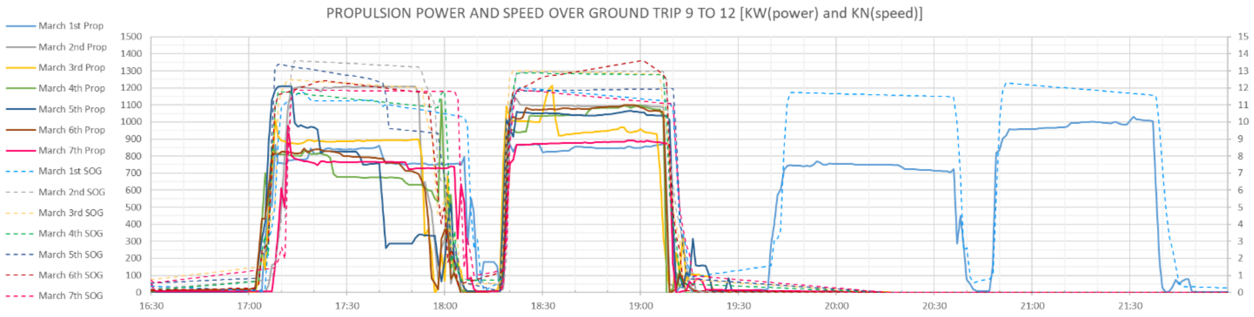


Figure 32 Propulsion Power (left axis) and Speed Over Ground (right axis) for fifth and sixth roundtrip (Sunday) first week of March

Figures 32-34 show that the general pattern of operating the E-ferry prototype is to maintain a certain speed, somewhere between 11 and 13 knots on both the leg to Fynshav and the return leg to Søby. But where the same speed is maintained, the power demand from engines typically differ from one leg to the other, most often with the leg to Fynshav requiring less power to maintain the set speed, than the return leg from Fynshav to Søby, due to wind direction and current. The difference is perhaps particularly evident in Figure 34, where the 6th trip sailed on Sunday, indicated in blue lines, shows a power demand difference of close to 200 kW, between the two legs. In fact, Sunday March 10, was a very windy day, with wind conditions over 20 knots true wind speed and the pattern of higher power demand on the return trip to Søby than on the leg out of Søby to Fynshav was observable for the whole day, as also illustrated in Figure 33, below, with speed over ground and power demand plotted for the first two trips.

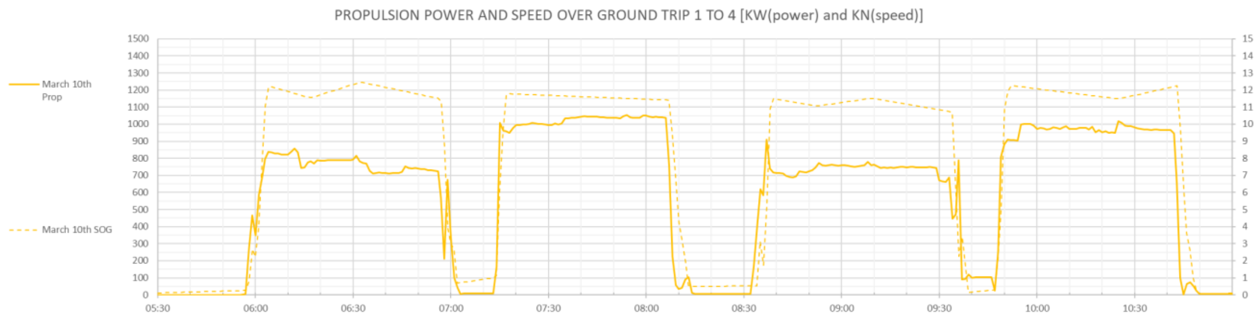


Figure 33 Propulsion Power (left axis) and Speed Over Ground (right axis) for first and second roundtrip (Sunday) first week of March

Neither speed losses, nor increased consumption of energy in windy weather thus seems to apply – or indeed account for any variation in the consumption of energy, as the higher demand for energy on one leg is typically cancelled out by a lower consumption on the other leg. This is not to say that the E-ferry – as is indeed the case for all other ferries operating in open waters – is not affected by wind conditions. Typically, wind speeds above 30-40 knots with wave heights of above 1.5 meters and from certain directions (east-east and west-west) are so problematic for the route from Søby to Fynshav that it leads to cancellations, whereas lower wind speeds e.g. from 20-30 knots will typically cause delays, due to increased manoeuvring time required to access the rather restricted harbours of both Søby and Fynshav. As can also be gaged from e.g. Figure 35, crew typically does not attempt to compensate for such delays by increasing the speed of the sea crossing itself, presumably because high speeds in heavy weather can cause parametric rolling of the ship, which combined with the E-ferry's very high stability, makes the journey very uncomfortable for passengers and can also cause extreme movement of ship's cargo on the car deck.

A final factor that has been considered as possibly explaining the variation in energy consumption from trip to trip is load of cargo. In terms of relationship between load and energy consumption, the basic assumption would be that the more load and hence higher draught that the E-ferry – like any other vessel – operates with, the more energy it will consume to carry the load from harbour to harbour. The conditional formatting and analysis of this relationship as illustrated in Figure 29 above, however, cannot conclude that there is such a correlation for the E-ferry; as was the case for the energy consumption in relation to wind speed, we find both low and high energy consumption with heavy load (100-140 tons) and both low and high energy consumption with lighter load. The underlying reason for the lack of correlation might be found in the fact that the design trim of the E-ferry is not ideal, as the battery system and power/charging cables to same added more weight to the starboard and fore sides of the final prototype. When operating with low loading conditions, the E-ferry trim is thus slightly on the nose, but when heavy loads are placed aft, the trim is improved and this seems to compensate for the extra energy that it would be assumed was required to move a heavier load. An indication that this hypothesis is likely to be correct can be found in Figure 34, where the draught aft has been plotted in relation to speed. Yellow lines and dots register the data at high draught, i.e. heavy load to the aft, green registers the data at low draught and correspondingly light load.

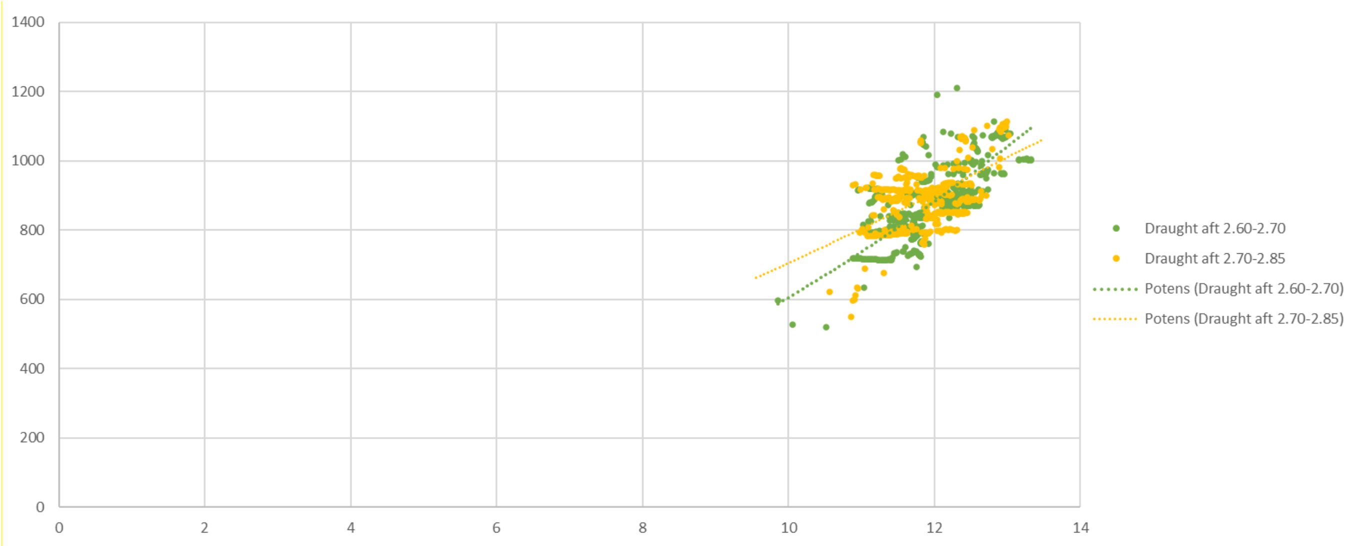


Figure 34 Speed as a function of power for light (green) and heavy (yellow) draught conditions aft. All data plots are selected for wind conditions below 10 knots representing calm conditions.

If the hypothesis of improved trim with heavy load is correct, which Figure 34 certainly indicates, then this of course also indicates that the 'neutral' unloaded trim of the E-ferry is not ideal. As noted above, this trim is the result of some design changes being implemented due to the innovative nature of the E-ferry prototype and in particular the aspects relating directly to the electrification, i.e. the battery system and the charging system's location at the fore and starboard side of the ship. While the overall design of a second iteration of the E-ferry prototype should certainly be adjusted to compensate for the added weight in these specific areas, potentially by adding trim tanks volume or through other design alterations, the less than ideal trim of the E-ferry prototype has nevertheless not resulted in a level of energy consumption per trip over the expected/required.

5.1.7 Emergency reserve

The emergency reserve of energy that is at all time maintained on the E-ferry prototype's battery system(s) is the E-ferry solution to the otherwise existing Class and Flag rules that require any vessel of the type to be equipped with an emergency (diesel) generator that can supply the ship with enough energy to maintain emergency procedures and return safely to port, in case e.g. the vessel's main power supply fails. As indicated in Table 9, the emergency reserve or 'energy reservation for emergency consumption' was originally set to 2x120 kWh, in addition to this it was proposed that 750 kWh in total should be available to make the E-ferry able to return to port in an emergency situation. The final criteria for defining and calculating the emergency reserve was developed and set during the design and approval phase, as part of the Design Team actions required for the approval of the E-ferry alternative design (IMO MSc. 1455). It was here determined that to be approved without a traditional emergency (diesel) generator, the E-ferry prototype would have to define each of the redundant battery rooms/systems as serving as an emergency generator, i.e. in case of one battery room failing, the other battery room should at all times be able to supply enough energy to the ship to (a) maintain all critical systems and emergency procedures (e.g. firefighting) for three hours. Moreover, to secure that the emergency reserve would be available throughout the battery life-time, the calculation of the energy reserve would have to be based on a battery system with 80% SoH. Based on an emergency capacity test, the final emergency reserve that has been set for each of the E-ferry battery rooms is now 396,6 kWh (400 kWh). On one hand, this is significantly higher than the initial calculations of 120 kWh on each room, but if we include the reserve of 750/2 kWh to be reserved for safe return to port, the total original energy reserve originally proposed was in fact closer to 500 kWh per room. The energy reserve capacity requirement of 400 kWh has been implemented in the E-ferry prototype IAS, and while the emergency reserve is of course always available for the crew to use in case of emergency or other unforeseen situations, an alarm will notify the crew when the level is crossed, just as there will be an automatic reduction on power load to engines, to safe the remaining energy. The limit for the emergency reserve is in any case below the recommended Depth-of-Discharge level (645 kWh), which the E-ferry prototype and its crew in any case seek to avoid breaching, at least on a routine basis. Figure 35 below illustrates how – as also indicated by Figure *24* above, the E-ferry prototype, even when operating at the most challenging 5 trip schedule routinely avoids breaching the DoD-level of 645 kWh per battery room and consequently also leaves the emergency reserve intact for use only for its intended purpose, i.e. when there is an emergency.

![eFerry logo]

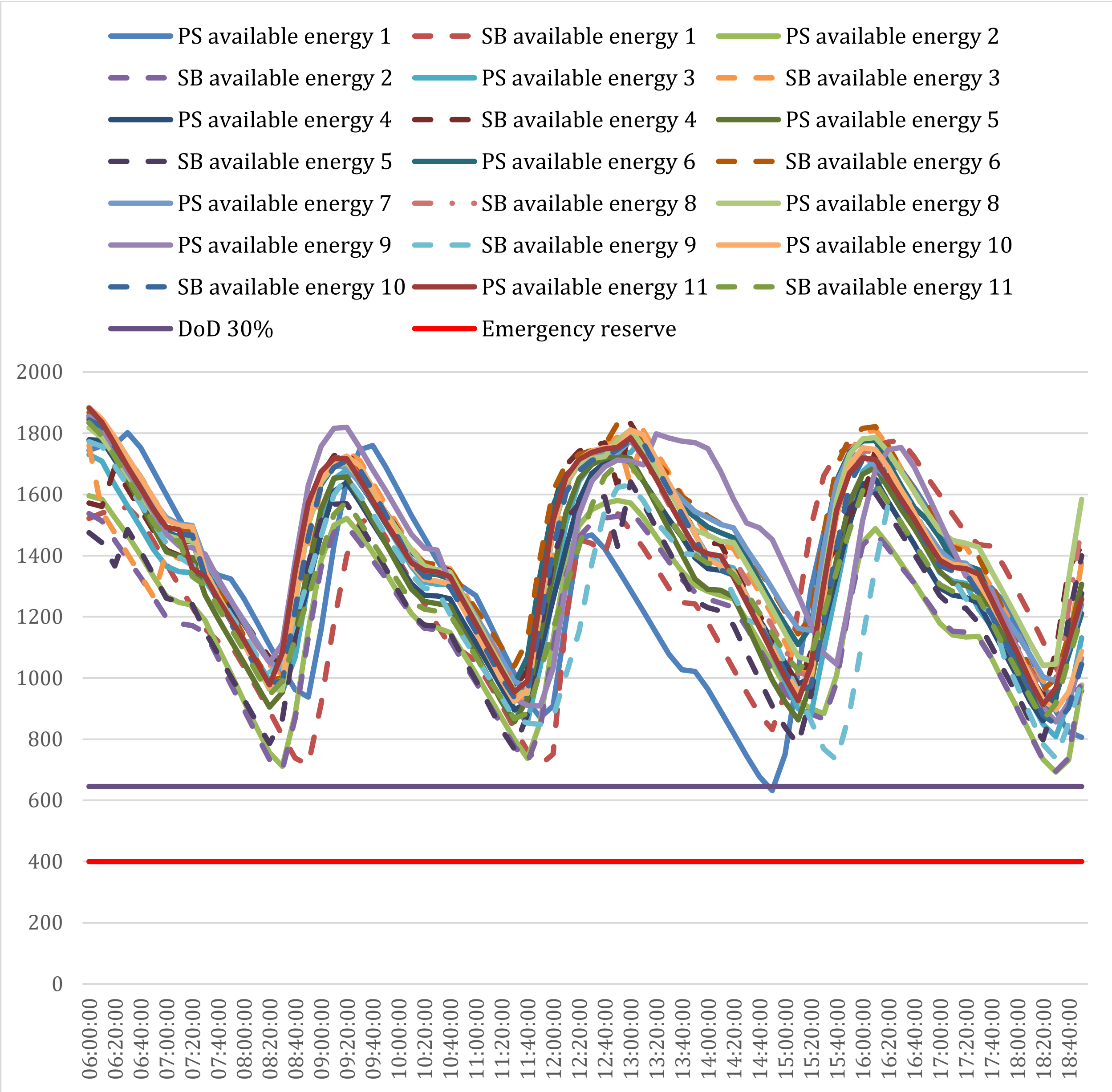


Figure 35 Emergency reserve level remaining intact on the most challenging E-ferry schedule of 5 return trips within 13.5 hours.

5.1.8 Charging effect

Initially, the charging effect was specified as 4 MW, supplied via 4 separate charging lines, each of 1 MW (at 780 VDC/1280 A). This entails that the maximum transferred energy from shore to batteries would be 66.6 kWh per minute, not accounting for any losses that may occur during the charging. As illustrated in Figure 36, which provides the energy transfer per minute during the four charging breaks of April 24, 2020, the actual maximum energy transferred is closer to 60 kWh.

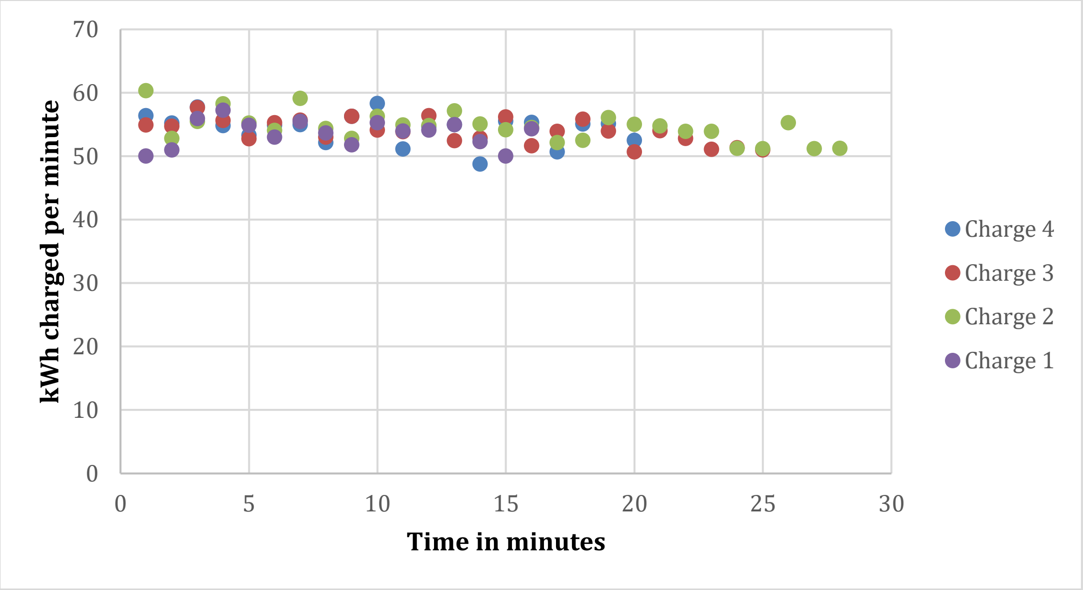
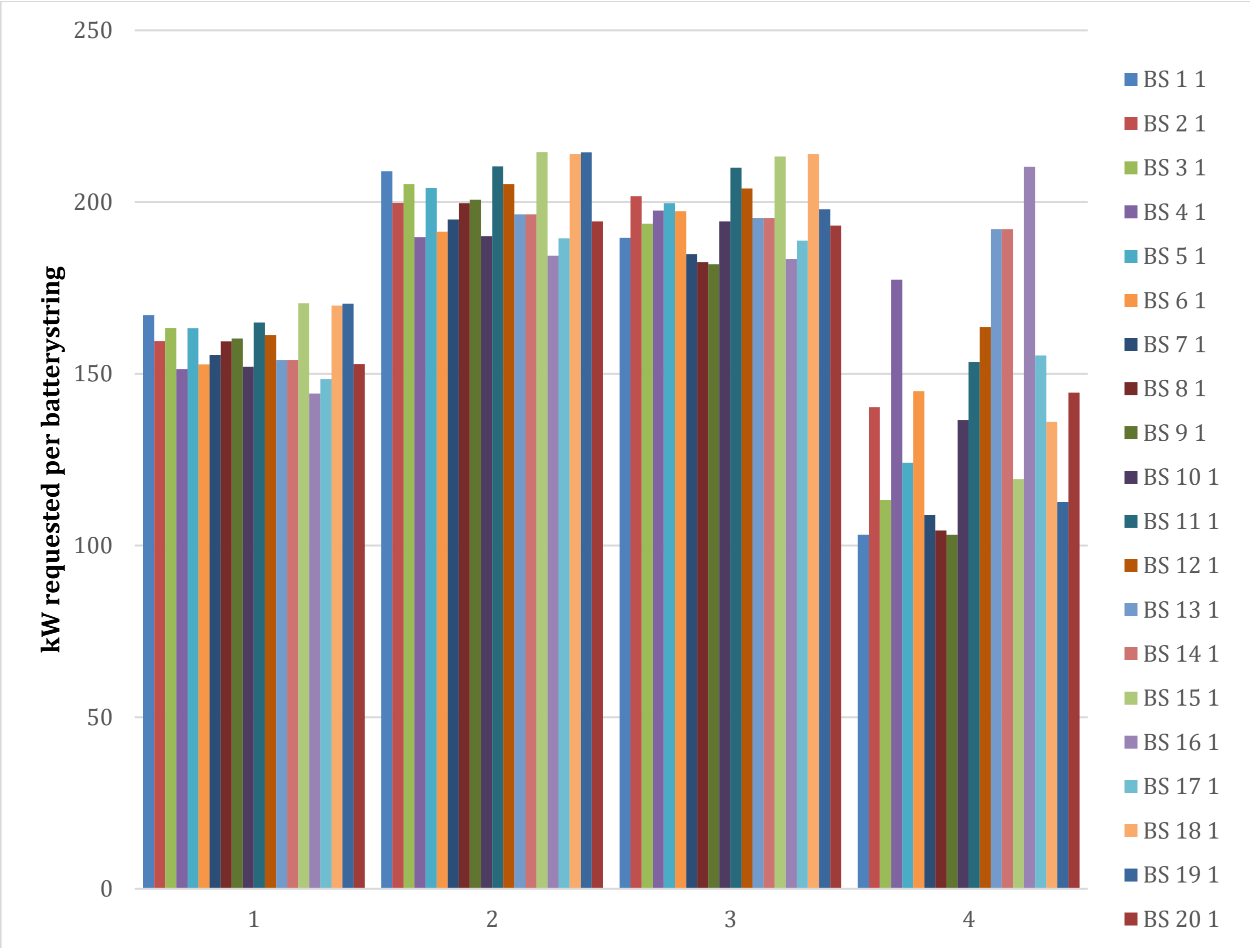


Figure 36: Charged kWh per minute, four charging breaks on April 24

The information about charged energy per minute is extracted directly from the Power Management System on board the ship, which does not take into account, any potential losses that occur. Losses and efficiency are discussed in more detail in sections below, where the energy efficiency from shore to batteries (i.e. charging) has been calculated to be a factor 0,92, or a loss of 8%. Based on the comparison between the expected maximum charge per minute of 66.6 kWh hours and the maximum achieved charge illustrated in Figure 38 of 60 kWh per minute, the deviation is about 9.9 %, which is slightly higher than the calculated loss. However, the 9.9 % deviation here does in all likelihood not indicate a 9.9% loss, but rather some impreciseness in the data input, in particular on the side of the frequency inverters (both shore side and ship side), which can deviate as much as +/-10% in terms of values provided for the data input. Moreover, the value of charged kWh per minute which is used to calculate the charging effect is also contingent on how much energy (current) is ‘requested’ by the battery system(s). As illustrated in Figure 37, below, for instance, the overall ‘demand’ from each of the 20 independent battery strings may thus vary somewhat, when comparing between them.



250
200
150
100
50
0
kW requested per batterystring
1
2
3
4
BS 1 1
BS 2 1
BS 3 1
BS 4 1
BS 5 1
BS 6 1
BS 7 1
BS 8 1
BS 9 1
BS 10 1
BS 11 1
BS 12 1
BS 13 1
BS 14 1
BS 15 1
BS 16 1
BS 17 1
BS 18 1
BS 19 1
BS 20 1

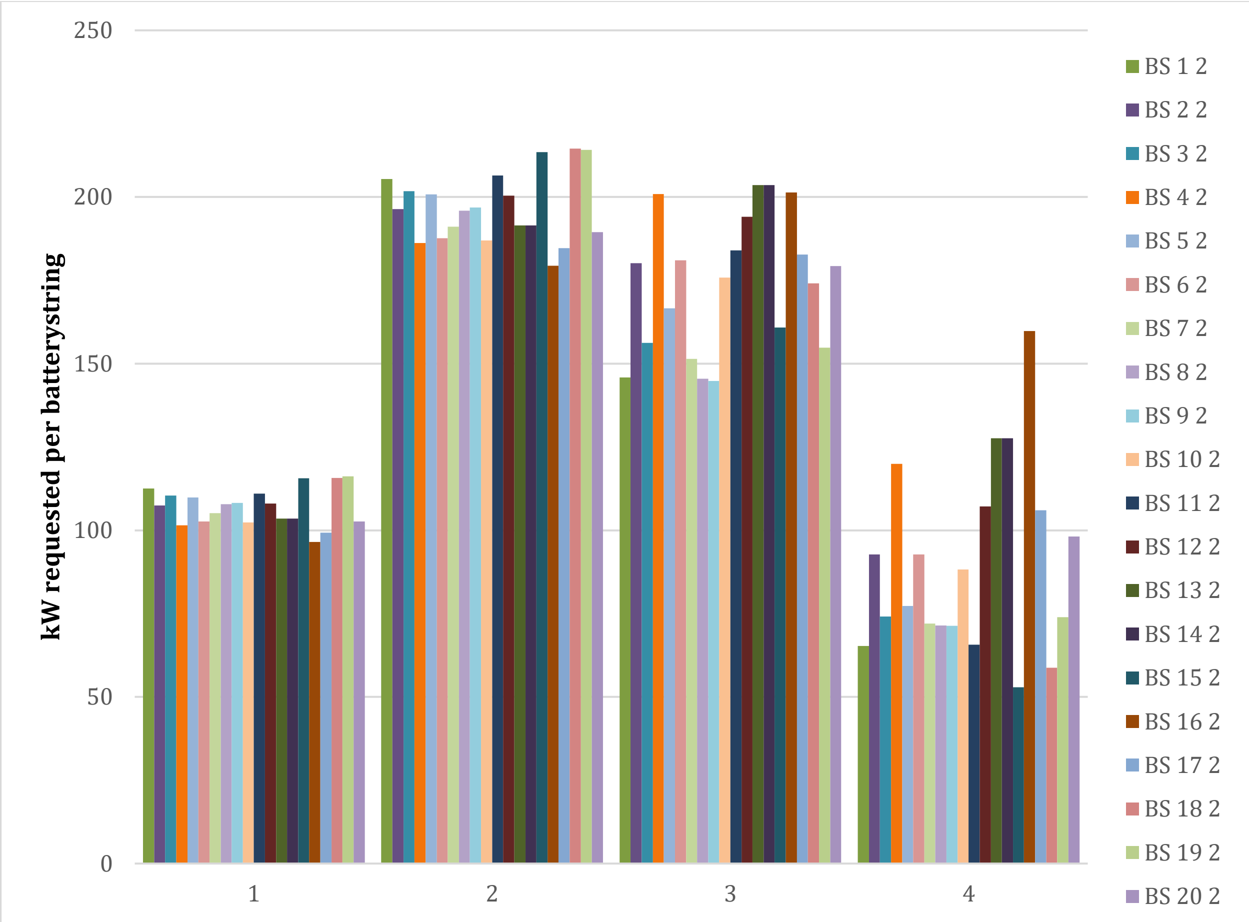


Figure 37: Power demand (per 10 minutes) from each battery string during two charging breaks on March 19

The data for Figure 37 has been extracted for two charging breaks, with entry points for every 10 minutes, of how much power (kW) each battery string is being supplied with – and hence how much power each battery string is demanding at the given time. While the 10 minutes intervals does introduce some degree of uncertainty to the data, the two figures nevertheless quite well illustrate the general pattern that whereas some battery strings during the two breaks were demanding the full effect of 215 kW (BS 15, 18 and 19), most demand or receive around 200 kW and others only between 180-190 kW. This is here taken to indicate that not all battery strings are demanding and/or receiving the full theoretical effect of 215 kW each, which might also (along with the charging losses) account for why the system as a whole does not consistently provide the full maximum of 66 kWh per minute during charging.

Figure 39 also illustrates a more general aspect of the charging that is particularly relevant to consider from an operational point of view, namely that the charging effect as a whole is dependent on the overall State-of-Charge of the battery rooms (and as such on the State-of-Charge of each string as well). Thus, the full charging effect of up to 4 MW is in fact only available – or requested – when the overall State-of-Charge is below 80% % (here based on maximum achieved capacity of 3.8 MWh, as discussed in section 5.1.6). Thus, as illustrated in Figure 38, the energy delivered from the charging system is typically around the maximum 60 kWh per minutes until a battery room has reached a State-of-Charge of 80 %, after which the charging effect ramps down.

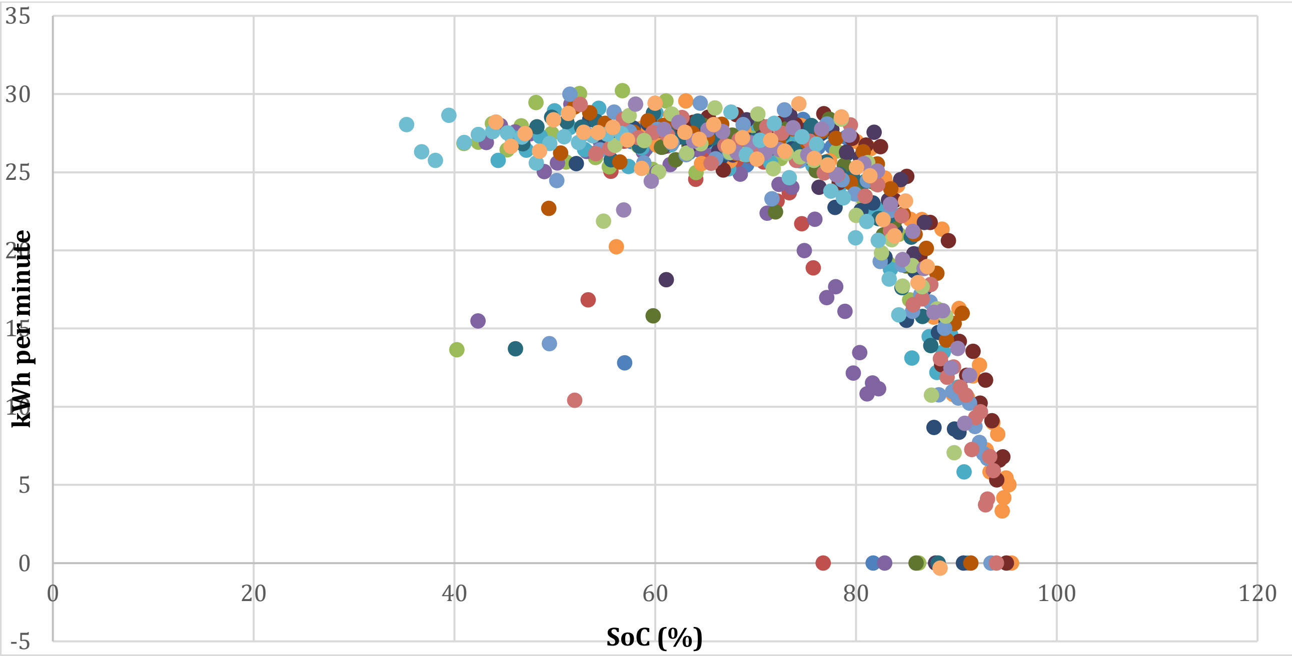


Figure 38: Charging effect in relation to State-of-Charge

In Figure 38, the charged kWh per minute has been extracted from the data collection system and plotted in relation to the overall State-of-Charge at the same time. Data was extracted from a total of 9 charging breaks in April 2020, where no major technical issues were in play with respect to either charging or battery systems, this to provide as optimal a picture as possible. The overall curve generated is relatively clear, with the outliers representing glitches and impreciseness because of the timing of the extraction and logging of data. What the curve indicates is, that the maximum charging effect of about 2 MW per battery room, or 30 kWh per minute for same, is available and/or requested up until a SoC of 65 % (equalling 1235 kWh per room, or a total of 2470 kWh in total). From 65% to about 80%, the effect is only slightly reduced, and between 28-29 kWh per minute is charged per battery room, this equalling an effect of up to 1740 MW per room. From 80% SoC and upwards, there is a steady decline in charging effect, and at 90% the charging effect has been halved to no more than 15 kWh per minute per room, equalling an effect of 900 kW.

The ramping down of the charging effect in relation to State-of-Charge illustrated in Figure 38 is more or less as expected, given that this is a natural consequence of how battery management systems and power management systems are designed to control the charging effect to which the batteries are subjected, to avoid over heating or loss of control of current levels, as well as to maintain a long life time of the batteries. The E-ferry as a whole, and in particular the E-ferry energy balance has been designed to take this into account, as illustrated in the original energy balance of *Figure 17* above, there was never any intention to charge the E-ferry up to its full capacity during the daily operation, but rather to stay continuously within the 30-80% State-of-Charge boundaries which are both relevant for prolonging the life time of batteries. Nevertheless, the actual curve for the charging effect is of strong relevance for the operator and crew of the E-ferry, as it provides some indications as to how the most efficient operating schedule can be planned and also some pointers as to what to do in case of delays occurring.

For instance – as listed in *Table 12* the current E-ferry schedule includes charging/harbour breaks in Søby of between 25-45 minutes.

Table 12: *Current operation schedule for E-ferry prototype*

Departure Søby	Sailing time	Arrival Fynshav	Harbour time Fynshav	Departure Fynshav	Sailing time	Arrival Søby	Harbour (and charging) time Søby
06:00	60 min	07:00	10 min	7:10	55 min	8:05	25 min
08:30	60 min	09:30	15 min	9:45	55 min	10:40	40 min
11:20	60 min	12:20	15 min	12:35	55 min	13:30	45 min
14:15	60 min	15:15	15 min	15:30	55 min	16:25	40 min
17:05	60 min	18:05	15 min	18:20	55 min	19:15	N/A[3]

With an effective charging time of five minutes less, to allow for the connect and disconnect procedures, the E-ferry is charged with between 1100-1700 kWh on each of these breaks, depending both on the SoC when charging is initiated and the time of charging. A single day's charging breaks and pattern is illustrated in Figure 39, below.

[3] *After the last trip, the E-ferry is slow charged over night.*

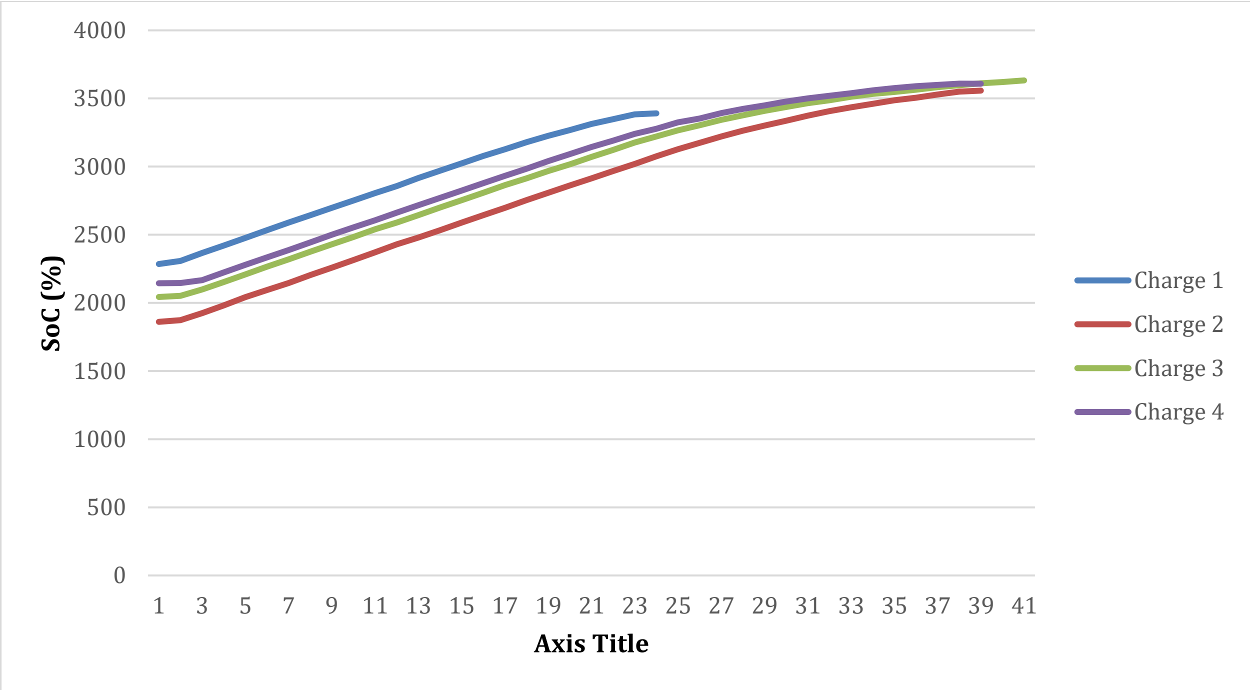


Figure 39: Charging break pattern in relation to operation schedule, April 1, 2020

As noted above, charging is most effective below 80% State-of-Charge (300 kWh) and in Figure 41 we can see this implemented by a slight flattening out of each of the 4 lines when reaching above 3000 kWh. Naturally, the higher State-of-Charge that the E-ferry batteries have before starting charging, the quicker will the 80% level be reached; after the first trip (Charge 1) after approximately 15 minutes, after the second trip (Charge 2) after about 23 minutes, with the third and fourth trip lying somewhere in between the two, with 20 and 18 minutes respectively. In combination with the length of time during which charging is continued past the 3000 kWh and the consequent loss in efficiency, the four charging breaks of an operation day for the E-ferry ends up with very different efficiencies with respect to average number of kWh that are charged per minute. *Table 13* illustrates this efficiency, again for a single day, April 1, 2020.

Table 13: *Efficiency of charging time with current E-ferry operation schedule*

Charging break no	SoC at charging start	Minutes charged	kWh charged	kWh per minute average
1	60%	24	1105	46 kWh/min
2	49%	39	1696	43.5 kWh/min
3	54%	41	1589	38.8 kWh/min
4	56%	39	1463	37.5 kWh/min

As indicated in Table 13, both State-of-Charge status at beginning of charging and the length of time at which charging is continued beyond the 80% charge of state has an effect on the efficiency of the charging time, so that the higher the State of Charge is, and the longer charging is continued past the 80% level, the less efficient the charging is. For the E-ferry operator in particular, charging break number 3 and 4 could both be reduced with up to 10 minutes without any serious effect on the overall energy balance, as both are currently long charging periods of 39-41 minutes, starting at relatively high charge of state, above 50%. As noted above, however, commercial operation schedules also need to consider other factors, and the economical savings of changing the schedule in order to reduce charging and crew-working time is in that respect probably negligible.

On the other hand, knowing the relationship between charging efficiency relative to length of time of charging and State-of-Charge levels could prove helpful for crew in terms of foreshadowing and determining what would be the best measures to take in situations where a delay has occurred, e.g. whether to attempt to mitigate the delay by increasing the speed of the E-ferry with an increased consumption of energy as a consequence, or by shortening one or more charging breaks.

5.1.9 Energy losses and efficiency

Initially, the energy losses or energy efficiency factor, was set at respectively, 0,95 from charging (or grid) to batteries, and 0,92 from batteries to propeller, an estimate of a total loss from transformers to propellers of 0,87.

The overall technical evaluation of the E-ferry prototype largely confirms these estimated numbers, when taking also into account that a number of extra components (e.g. filters) were added to the initial design.

Energy losses (or efficiencies) are first divided into those losses related to charging, i.e. from grid to batteries, and those related to power consumption during operation, i.e. from batteries to propeller shaft.

Charging losses originates from at least four sources:

(a) The AC/DC inverters and AC sinus noise filters– these components being part of the system that transforms the AC shore power to DC before charging. Estimates provided by E-ferry partner Danfoss is that these introduce a loss of around 2% at high effect charging.
(b) The cables carrying the DC power from shore to ship (an onboard the ship to DC/DC drives) and through the 32 pin plug on the E-ferry ramp have been estimated to a loss of 1.5%, but this may vary significantly depending on how the cables are laid and in particular how much resistance and heat is developed in the cables.
(c) Losses in the DC bus and DC/DC drives, both onboard have been estimated at 2%, again by E-ferry partner Danfoss who have also supplied these components.
(d) Losses in batteries and battery system have been estimated by E-ferry partner Leclanché as 1.5%. Lithium-ion batteries, when new, have an extremely high coulombic efficiency of above 99,9 %. When batteries have aged or are dealt with in manners out of specification, internal resistance will increase and State Of Health (SOH) will decrease, with a resulting increase in energy losses. At the SOH levels (80%) needed for the operational life of E-ferry, coulombic efficiencies will, however, still be close to 99% at end-of-life. Losses therefore originates mainly

from the current flow of transporting energy in and out of the battery cells and subsystems within the battery pack collecting current and controlling the battery charge and discharge, and will be dependent on aspects such as battery voltage, temperature and C-rate.

The potential losses identified and estimated above leads to a slightly higher energy loss from grid to batteries than was previously estimated, namely 0,92 as compared to 0,95. To confirm these estimates, a comparison was made between the amount of energy measured at the electricity supplier's meter in the transformer house and the amount of energy registered to be stored on the batteries during 4 charging breaks on two consecutive days in September, 2019. The comparison is provided in Table *14*, below, with charging efficiency factor indicated for each charging break. Note that the energy supplied as hotel power by-passes the batteries during charging and has hence been subtracted, as also indicated in the table.

Table 14: *Efficiency of charging time with current E-ferry operation schedule*

Charging period		**Invoice supplier**	**Hotel power**	**Added to batteries**	**Charging efficiency**
Date	After roundtrip	*kWh*	*kWh*	*kWh*	*factor*
Sep. 5th	1	1770	78	1548	**0,92**
Sep. 5th	2	1763	66	1552	**0,92**
Sep. 5th	3	2328	119	2021	**0,92**
Sep. 5th	4	1788	78	1567	**0,92**
Sep. 6th	1	1781	51	1550	**0,90**
Sep. 6th	2	1999	93	1785	**0,94**
Sep. 6th	3	2337	93	2036	**0,91**
Sep. 6th	4	2082	76	1811	0,91
				Average:	**0,92**

The variation in Table 14 with respect to the efficiency factor from break to break could be a reflection of the many variables that may affect the efficiency, e.g. issues such as temperatures in cables and batteries that may change from day to day to day. More likely, however is, that the variation is due to the uncertainties and inaccuracies inherent in the measurements and components from which these measurements are made. Output values from AC/DC inverters are intended as guiding for the control readings and have neither the resolution nor the accuracy for detailed data analysis, but can deviate with as much as +/- 10%, according to Danfoss. Also, the battery State-Of-Charge measurements are based on very small differences in battery voltage and algorithms changing with C-rates, State Of Health and temperature. Thus, the start and end point for any charging session together with the charging speed will affect the accuracy of measurements at the battery level. Nevertheless, as the variation across the 8 charging breaks sourced is within reasonable limits, and moreover matches the original expectancies quite well, the efficiency factor of 0,92 that is found as an average in Table 14, is taken to be a reliable measure of the energy efficiency of the E-ferry charging system, i.e. the transforming and channeling of power from shore to ship.

While a deviation of 0,03 (or 3%) with respect to energy loss from shore to ship is technically negligible, from an operators point of perspective, there could be some economical gains from investigating exactly where the respective losses emerge. According to energy supplier, for instance, the measurements provided from their meter (supply transformer meter) and invoiced to the Aeroe-ferries in fact include up to 4% surcharge, which the energy supplier is allowed by law to add to every invoice for electricity in Denmark, to cover uncertainties and own losses. The 3% deviation in losses we have found on the E-ferry could thus be accounted for in this manner and it would probably be a political and legal matter to attempt to get dispensation for paying the surcharge, e.g. as a big consumer. An alternative, which is not possible for the E-ferry operator Aeroe-ferries at this point, but could be relevant for future operators of E-ferries, would be to build, own and operate the 10kVA grid transformer directly, as this would introduce some savings (and fewer losses) to the electricity bill, because the E-ferry operator would be considered an electricity customer of the B-high category, with savings of around 12% on energy costs for the E-ferry prototype per year. In addition to this, the one-time connection fee would also be eliminated *and* eliminate the one-time connection fee. The investment cost of establishing the connection would then of course have to be taken into account, and will vary depending on the distance from charging system/harbour to the nearest high voltage supply transformer.

Below are presented an estimate of costs for the E-ferry prototype electrical infrastructure in Søby (*Table 15*), where distance to nearest transformer is <3 kilometres. As evidenced when comparing to the cost of the one-time connection fee of 1.383.157 Euro (See section 5.2.1), the savings would in fact for the E-ferry prototype have been immediate, at around 35% or close to 500.000 Euro. In addition to this then come the estimated operational energy cost savings of 12% that would apply as a B-high customer.

Table 15: ***Estimated cost to establish 10kVA/0,4kVA transformer in Søby to obtain B-high customer status and tariff***

Investment to obtain customer type B-high connection	Cost (€)
Four 10kVA/0,4 kVA power or distribution transformers	402.685
Transformer enclosure and housing	174.497
10 kVA AC cabling 3 kilometres	120.805
Connection fee distribution transformer	4.698
Installation and VAT	193.238
Total cost	895.923

Energy losses from the drivetrain, i.e. those related to power consumption during operation originate primarily from 4 sources:

a) Losses in batteries and battery system (indicated with F in Figure 43), which have been estimated to 0,5%, which is lower than the loss expected from the batteries during charging, as C-rates are much lower (typically around or below 0.5 C) during discharge than charge.
b) Losses in DC/DC drives and DC bus are estimated at 1.5%, again lower than the loss during charging, due to lower C-rate.
c) Losses in DC/AC inverters that transform the DC battery electricity back to AC for the motors, estimated at 1.5%, though depending on the engine load.
d) Losses in motor – the AC Synchronous Reluctance Assisted Permanent Magnet Motors are second-to-none when it comes to the efficiency of electric motors and is specified by Danfoss to have losses around 3-4%
e) Losses in mechanical gear, with a gear ratio of 1:4, estimated at 1-1.5%

The potential losses identified and estimated above leads to a similar energy loss from batteries to propulsion, namely 0,92-0,93 as compared to 0,92. These efficiency values are also supported by accumulated experience from diesel-electric drivetrains, where the main difference from the E-ferry prototype is that the generator (see Figure 40 below) is a diesel-engine, where the E-ferry has batteries.

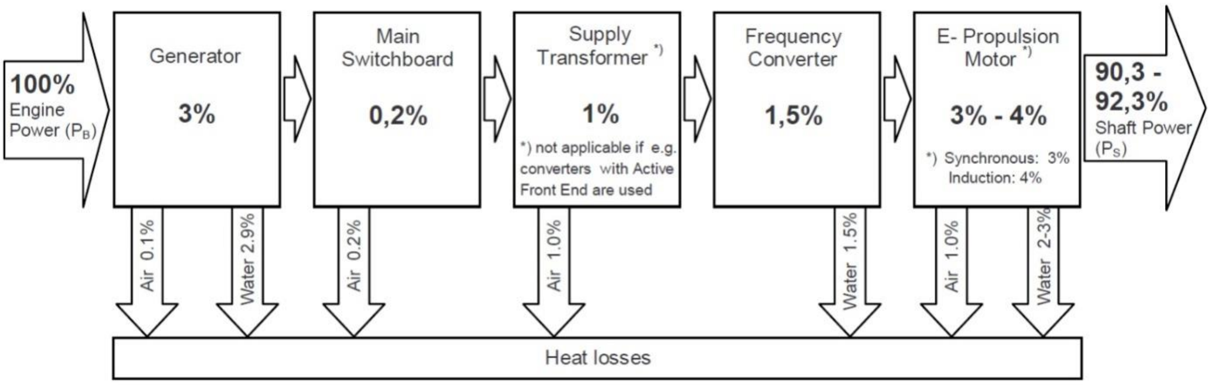


Figure 40 Drive train losses in Diesel-electric drive train with Diesel generator powered energy source, (MAN, Diesel electric drives - Guideline).

In contrast to the control calculations of losses from shore grid to batteries, it has not been directly possible to measure the losses in a similar fashion from batteries to propel. As noted above, any direct measurements from the Danfoss drives and inverters inherently carry with them a degree of variation and uncertain that is too high to analyse detailed and low-value efficiency effects. This was confirmed when an attempt was nevertheless made, and the values found were not only fluctuating in inexplicable manners, but also at times providing efficiency values of above 1.0. Observations made during the sea trial and specifically the speed measurement tests, however, goes some way to suggest that the real efficiency factor for the E-ferry drive train is in fact higher than estimated above. The speed measurement test was done in calm water with full 2x700 kW engine powers, with a speed of 14.3 knots obtained. This result corresponded well to two of the three theoretical speed-power curves foreseen. Put together, the energy consumption observed during the speed test indicates that the efficiency of the E-ferry prototype, from battery to propeller is in fact higher than the calculated 0,92, even at very high loads, whereas it would be expected – for a fully electrical drivetrain in contrast to a diesel-electric system – that the efficiency would be even higher at lower loads.

5.1.10 KPI – technical evaluation

In order to summarize the main findings of the technical evaluation of the E-Ferry, the following Key Performance Indicators (KPIs) are assessed:

Table 16: ***KPIs assessed for Technical Evaluation***

	Indicator	Unit	Need/Expectancy	E-ferry prototype	Comments
1	Nominal battery capacity	MWh	4.1 MWh	4.3-4.4 MWh	Real available capacity of 3.8 MWh
2	Average energy use per return trip	kWh	1750 kWh	1600 kWh	Somewhat big variation in individual trip consumption presumably due to alternate operation strategies
3	Energy efficiency	%	87,4%	87%	Could possibly be improved by investigating whether 4% is due to supplier's measurements
4	Energy reserve	kWh	240 kWh	400 kWh	Below DoD recommendations and calculated for end-of-life SoH with 80% capacity
5	Charging effect	MW	4 MW	4 MW	Maximum effect, dependent on battery SoC and SoH

5.2 E-ferry economical evaluation

The E-ferry economical evaluation is intended to not only report the construction and operating costs of the E-ferry prototype, but also to compare these costs with the costs of operating the same or similar route with alternative vessels, either a new built conventional diesel-electric vessel or an existing, older vessel of similar performance. To make the comparisons as fair and as realistic as possible, the economical evaluation of the E-ferry prototype has been based on the costs applying for the late stages of the E-ferry prototype evaluation period, when the E-ferry can be considered a viable alternative to a vessel in ordinary and reliable operation.

Furthermore, the comparable alternative vessel has been adjusted as best as possible to fit the same – or similar - operational pattern as the E-ferry prototype, e.g. with respect to capacity, safety, speed and frequency of operation. For each of the cost categories provided, we have attempted to provide the underlying rationale for our calculations, to provide as much clarity as possible to our comparisons. E-ferry construction and operating costs are provided first (section 5.2.1 and 5.3 respectively), after which we provide the descriptions, calculations and costs for the two alternative vessels with which the E-ferry prototype is compared (sections 5.3.5.1 and 5.3.5.2, respectively). Section 5.3.6 concludes the Economical Evaluation by providing the comparison.

5.2.1 E-ferry construction costs

In order to calculate the overall construction cost of the E-ferry, the following cost items have been taken into consideration (Table 17):[4]

- Ferry design and drawings;
- Hull construction and outfitting costs;
- Batteries, battery racks and battery control units;
- Automation, electrical systems, propulsion and charging;
- Electrical infrastructure on-shore;
- Auto mooring;

***Table 17*: E-ferry construction costs per major item/contributor**

Cost item description	Cost in euros
Design, drawings and documentation	475.000
Hull production	2.642.000
Outfitting	7.161.511
Charging system on-shore	770.872
Electrical systems and propulsion	2.100.000
Battery system	4.283.276,52
Auto mooring x 3	1.720.109,04

[4] Throughout this document, for all numbers originally provided in DKK instead of Euro, an exchange rate of 7.45 has been applied.

Electrical infrastructure	297.630,85
One time connection fee	1.383.157,32

In addition to the costs listed above, the operator has also had costs connected with the overall on-shore facilities (estimated final costs at 3.495.000 Euro in all, for three harbours), but as these costs would have been involved for the implementation of any new ferry, not just the E-ferry, these costs are not used for the comparative economic evaluation. The construction costs that are specific to the E-ferry have subsequently been merged into 4 larger categories; (a) the vessel itself, (b) electrical charging infrastructure, (c) auto mooring, and (d) one time connection fee. The reason for separating these costs categories for the evaluation is, that whereas the costs for (a) and (b) are cost specific to a fully electric vessel, cost (c) is optional and/or could be applied to other vessels as well and is furthermore dependent on how many harbours the vessel would dock at. Cost (d) is dependent on national regulations and may hence vary significantly for future projects. Moreover, whereas costs for the vessel and charging infrastructure also includes one-time development costs (estimated at 3,5 %), costs (c) and (d) does not. Table 18 below lists the overall costs for the E-ferry prototype based on these categorizations, as well as the total cost of the E-ferry including charging system and connection fee. As the automooring is in principle optional for the specific operator,[5] the cost of two such systems[6] has been added in a second calculation of total costs, in the same table.

***Table 18*: E-ferry construction costs per category**

Cost category	Included costs	Cost	Cost excluding development costs (3.5%)
Full electric E-ferry vessel	Design, hull, outfitting, battery system, propulsion, electrical system, automation, systems, approvals.	16.661.847,52	16.078.682,8
On-shore charging system	Charger, cables, inverters, housing, filters, cooling, VAT	1.068.502,85	1.031.105,25
One time connection fee	Fee for electricity supplier (establishing of 10 kV supply and	1.383.157,32	1.383.157,32

[5] *Note, however, that without automooring, manning requirements are likely to increase, with an increase in operation costs to follow).*

[6] *While the E-ferry prototype is built to operate on a so-called V-route, with three harbours for docking, many operators of ferries this size and type would only require 2 automooring systems as they would operate between two harbours only.*

	transformers), including VAT		
Total cost, E-ferry with charging and connection		**19.113.507**	**18.492.945**
Automooring	2 systems, including installation and VAT	1.146.739,4	1.146.739,4
Total costs including automooring for two harbours		**20.260.246**	**19.639.684**

Even when adjusted with the development costs of 3.5 %, the construction costs of the E-ferry prototype is *not* the cost that the construction of a new E-ferry of similar type and dimensions as the E-ferry prototype would cost today, should an operator decide to order a new built electrical ferry. According to the constructor of the E-ferry, building of a second E-ferry would be approximately 5% less cost, and a third up to 10% lower cost, due to economy of scale. This estimate does not take into account the big decrease in cost of marine batteries, especially over the last 5 years. The E-ferry batteries were purchased and priced at the beginning of the E-ferry project, in 2015, where the cost was around 1000 Euro/kWh, whereas the providing company is currently pricing the marine batteries at just over 500 Euro/kWh (see Figure 42) below, for how this increase in cost follows the overall pattern of the market).

From an investors point of view the E-ferry prototype thus still includes too many development and maturing cost of the technology and it does not reflect the economies of scale when going from prototype to a series of new buildings, nor the decrease in one of the significant cost categories, the battery system. Table 19 below lists the estimated construction/purchase costs for a third E-ferry in a series, as it would likely apply for a new investor, at today's prices.

Table 19: **E-ferry prototype and E-ferry no 3 at today's prices**

Cost category	Included cost	E-ferry prototype cost including charging station	E-ferry prototype cost excluding development costs (3,5%)	E-ferry series no.3 including charging station
Full electric E-ferry vessel	Design, hull, outfitting, propulsion, electrical system, automation, systems, approvals.	12.378.571,00	11.945.320,96	11.140.713,90
Battery system including BMS	Battery system incl. installation and approvals	4.283.276,52	4.133.361,84	2.109.718,00
On-shore charging system	Charger, cables, inverters, housing, filters, cooling, VAT	1.068.502,85	1.031.105,25	961.652,57
One time connection fee	Fee for electricity supplier (establishing of 10 kV supply and transformers), including VAT	1.383.157,32	1.383.157,32	1.383.157,32
Total cost, E-ferry with charging and connection		**19.113.507,20**	**18.492.945,3**	**15.595.241,8**
Automooring	2 systems, including installation and VAT	1.146.739,40	1.146.739,40	1.146.739,40
Total costs including automooring for two harbours		**20.260.247,09**	**19.639.684,77**	**16.254.746,68**

Similar savings in construction cost can, as discussed above in the Technical evaluation, in all likelihood be done if the operator chose to establish the electrical infrastructure themselves, this leading both to a 35% reduction of the one-time connection cost and a 12% saving on energy costs due to changed status as customer. The E-ferry prototype operational costs have been calculated based on information extracted from the Technical evaluation as well as information supplied directly from the E-ferry operator. As noted in E-ferry operation schedule, the E-ferry prototype has been tested and evaluated during the demonstration period under a number of different conditions and operating schedules. To give the best picture of the operating costs of the E-ferry prototype, as a vessel in ordinary operation under the conditions and expectations of the operator, the operating costs provided here are based on the 7th period of the demonstration phase. The operation costs are separated into three categories; crew costs, energy costs and general costs, for the reason of making the costs as transparent as possible and because each of these categories may show quite some variety from operator to operator, especially at an international level, where salaries may be lower or higher than in Denmark and certain taxes and fees may or may not apply.

5.3 E-ferry operational costs

5.3.1 E-ferry crew costs

During the 7th period of the evaluation phase, where the E-ferry prototype can be said to be in ordinary operation, sailing 5 return trips per day, it was manned with the approved safety crew of 3 crew members, consisting of a master, a chief officer and a third safety crew (catering person). For the overall calculation of crew costs, expenses have been calculated based on 14 hours shifts per day, with a total average of 420 operating hours per month. To cover 420 operating hours (and allow for vacation, illness and other staff relevancies), the operation of Ellen has thus been calculated to require between 3,1 and 3,24 crew shifts per month, depending on the crew category in question.[7] This means that each of the 3 persons in the crew will be working between 130 and 136 hours on average per month, in actual operation on board the E-ferry prototype. In addition to the general safety crew that is required by the maritime authorities to operate the vessel with passengers, the operator has chosen to allocate a full-time supporting engineer (155 hours per month) and a general maintenance support for 12 hours a week, or 48 hours a month. Table 20 lists the crew expenses for operating the E-ferry prototype one month and one year, respectively; wages for each crew category is based on average salaries and includes pension and other employee expenses paid by the employer. The average salaries have been calculated from standard wages across a group of smaller Danish ferry companies, as variation in individual salaries apply due to local and national agreements. Supporting land crew costs (office administration) have not been included in the overall costs, as these are not specific to the E-ferry prototype, but would apply to any type of vessel operating for a ferry company.

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[7] *Depending on crew category requirements, the effective operation hours for each category differ, especially for the Master, who is typically required to take time out of operation for training, to maintain essential papers for mastering a ship.*

***Table 20*: Crew costs for operating E-ferry prototype**

Crew category	Average salary and employee expenses DKK/EURO	Number of crew shifts required for one month of operation	Monthly cost DKK/EURO	Yearly cost DKK/EURO	Yearly cost including pay roll fee[8] DKK/EURO
Master *STCW regl. II/2 as master*	69.750/ 9.362,4	3,24	225.990/ 30.334,2	2.711.880/ 364.010,7	2.798.253,38 / 373.604,5
Chief officer *STCW regl. II/2 as chief officer*	60.450/ 8.114,1	3,17	191.626,5/ 25.721,7	2.299.518/ 308.660,1	2.372.757,6/ 318.491
Safety crew/catering *STCW regl. V/2 paragraph 5 and table A-VI/2-1*	37.200/ 4.993	3,10	115.320/ 15.479,2	1.383.840/ 185.750,3	1.427.915,3/ 191.666,5

[8] Pay roll fee or the so-called 'lønsumsudgift is a form of tax paid in lieu of VAT for passenger transportation. Both the VAT and pay roll fee vary for the individual operator, depending on transferred units and may also vary between operators. For the current purposes, the pay roll fee for Aeroe-ferries has been estimated at 6,37%, of which 50% is paid in lieu of VAT.

Service engineer *STCW regl. III/3 recommended*	58.590/ 7.864,4	1,00	58.590/ 7.864,4	703.080/ 94.373,2	725.473,1/ 97.378,9
Able seaman /maintenance crew *STCW regl. V/2 paragraph 5 if part of safety crew*	40.300/ 5.409	0.35	14.105/ 1.893,3	169.260/ 22.719,5	174.650,93/ 23.443,1
Total crew cost			**605.631,5/** **81.292,8**	**7.267.578/** **975.513,8**	**7.499.050,4** **1.006.583,9**

5.3.2 E-ferry energy costs

To calculate the electricity costs for the E-ferry prototype in operation, the same basic scenario of five daily trips as for the crew costs have been used. As illustrated in Section 4.1.3.1, the average consumption of the E-ferry for a return trip is 1600 kWh, this includes the energy used for the hotel load when sailing and at berth in Fynshav, where this energy is taken directly from the batteries, along with the energy for propulsion. As also calculated in Section 4.1.3.3, the efficiency from shore to batteries is a factor of 0,92, which means that to use 1600 kWh, at total of 1739,1 kWh will need to be supplied from the grid, per return trip. Furthermore, the hotel consumption, is, when the vessel is connected to the charger in Søby, both during the operational breaks for charging as well as during idle hours at night, supplied directly to the hotel switchboard and does thus not figure in the consumption data provided. The basic hotel load has been measured for the E-ferry to be 55 kW, which, when taking both charging breaks and idle hours into account, is supplied for 12.5 hours per day, again at an efficiency rate of 0.92, giving a total consumption on this part of the E-ferry system of 747,3 kWh per day. Total energy consumption for the E-ferry per day, with a 5 trip schedule is thus

9443 kWh.[9] Table 21 lists the electricity consumption per category, per day, and per year, as above calculated on the expectation of 5 return trips per day.[10]

***Table 21*: Energy consumption, E-ferry prototype, 5 return trips for 360 days per year**

Category of consumer	kWh per day, consumption	Including losses from charging	Total consumption per year
E-ferry propulsion and hotel load in operation and in Fynshav, 5 trips	8000 kWh	8695,7 kWh	3.130.452 kWh
Hotel consumption in Søby (charging and idle), 12.5 hours	687,5 kWh	747,3 kWh	269.021,74 kWh
Total	**8687,5**	**9443 kWh**	**3.339.480 kWh**

Costs per kWh are based on the Danish spot prices for electricity, and includes the fee for green electricity of 0,024 DKK/kWh (0,32 Euro cent/kWh) that is currently paid by the operator. Figure 41 illustrates the development of spot-prices over 9 months of the E-ferry demonstration period (including periods 1-6), from August 2019 to April 2020.

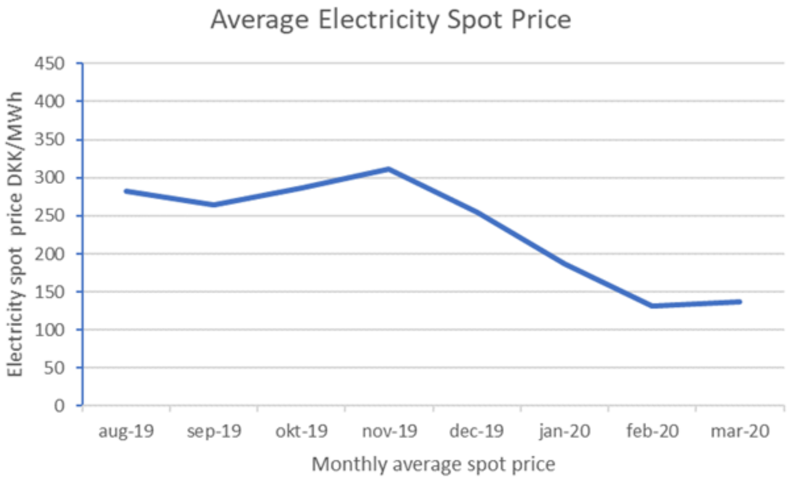

***Figure 41*: Development in spot prices Danish electricity August 2019-April 2020**

[9] Daily consumption here calculated deviates less than 1% +/- from the average daily consumption registered at meter, which is the consumption the operator gets billed for.
[10] Both here and for the comparison with alternative vessel, a full year of operation is set at 360 days, to allow for docking periods of up to 5 days with no consumption.

The electricity spot prices during the period from August 2019 to April 2020) is on average 231,65 DKK/MWh (31,1 Euro/MWh), which is slightly lower than – but still relative close to – the last five year average of 237,50 DKK/MWh (31,9 Euro/MWh). Thus, despite their somewhat volatile nature, spot prices during the demonstration period are fair to use for the comparative E-ferry evaluation.

Table 22 specifies the different cost categories of Danish electricity and Table 23 provides the final calculations for electricity costs for the E-ferry prototype, per day and per year.

***Table 22*: Cost categories for Danish electricity prices**

Electricity cost		
	B-low DKK per kWh	*B-high* DKK per kWh
Electricity spot price	0,2316*	0,2316*
Spot trading tariff	0,0050	0,0050
Wind Power certificates	0,0240	0,0240
Net tarif	0,0830	0,0252
Transmission tariff	0,0610**	0,0610**
System tariff	0,0360	0,0360
PSO-tariff Evonet	0,0260***	0,0260***
Minimum fee	0,0040****	0,0040****
Electricity VAT excluded	0,4706	0,4128
VAT 25%	0,1177	0,1032
Refundable VAT	0,0588*****	0,0516*****
Electricity price total	**0,5295**	**0,4644**

* DK 1 Spot price average demonstration period August 2019 to April 2020 – NordPool
** Notified price increase of 0,0017 DKK/kWh in transmission tariff from Energinet.dk included
*** Public Service Obligation tariff for 1st quarter 2020 (phased out in 2022)
**** According to EU exemption from 2013

***** Refundable VAT according to the split between tickets for persons and cars/goods (approximately half of 25 percent)

Table 23: **E-ferry energy costs, per day and per year**

Category of consumer	kWh per day	Cost at spot price per day DKK/Euro	Cost per day including fees, tariffs and taxes DKK/Euro	Cost at spot price, per year DKK/Euro	Cost per year, including fees, tariffs and taxes
E-ferry propulsion and hotel load in operation and in Fynshav, 5 trips	8695,7 kWh	2013,9/ 270,3	4604,4/ 618	725.004/ 97.316	1.657.584/ 222.494,5
Hotel consumption in Søby (charging and idle), 12.5 hours	747,3 kWh	173,1/ 23,2	395,7/ 53,1	62.316/ 8.364,6	142.452/ 19.121,1
Total	**9443 kWh**	**2187/ 293,5**	**5000,1/ 671,2**	**787.320/ 105.680,5**	**1.800.036/ 241.615,6**

5.3.3 E-ferry general costs

General costs, including maintenance costs, repairs, dockings and surveys of e.g. fleets, have been estimated by the operator, as actual costs for this cannot be provided for a vessel, which is yet to undergo its yearly docking and new surveys. The costs have been calculated for a five-year period, and then distributed over the same five years, in accordance with the operator's usual budgeting practice. In addition to maintenance costs, other general costs that apply are: insurance (ship and shore), "other expenses", which includes items such as VAT and taxes (except VAT and other fees on electricity, already included in the electricity costs and the salary fee in lieu of VAT which has already been included in the crew costs) and various taxes and fees. General costs per category are listed in Table 24, below.

***Table 24*: E-ferry general costs per year**

Cost category	Costs included	Cost in DKK	Cost in Euro
Maintenance costs	Estimated maintenance, service and repair on ship and charging system, surveys, dockings	1.702.000	228.456,38
Other expenses	Maintenance of on-shore installations (ramp, auto mooring etc.), various crew expenses, ticketing equipment, some taxes and fees etc.	1.173.752	157.550,60
Insurance	Ship and shore/charging system	592.000	79.463,09
Total general costs		**3.467.752**	**465.470,07**

The total yearly costs of operating the E-ferry five trips a day, every day, is listed in Table 25 below.

***Table 25*: E-ferry yearly operation costs for five trips per day, every day**

Cost category	Included costs	Cost in DKK	Cost in EURO
Operating crew costs	3 crew, as approved, including two navigators and a catering crew with safety papers, 14 hours	6.598.926,3	885.761,92

	shift per day. Total crew required for a month's operation is 3x3. Including salary fee.		
Supporting crew	One engineer/technician, full time position (155 hours per month), one able body/maintenance crew, 48 hours per month. Including salary fee.	900.124,03	120.822,02
Energy consumption, operating time	Actual energy use for 14 hours of operation, including hotel consumption during harbour stays in Fynshav	1.657.584	222.494,5
Energy consumption idle time	Actual energy use for 12,5 hours of idle time port stay and night in Søby with hotel consumption	142.452	19.121,1
Maintenance costs	Estimated repair and replacement costs, dockings, surveys and service	1.702.000	228.456,38
Insurance	Ship and shore	592.000	79.463,09
Other expenses	Operation and maintenance of ramps, various crew expenses, ticketing equipment, shore supply for idle hours etc.	1.173.752	157.550,60
Total costs	**Per year, for operation with five**	**12.766.838**	**1.713.669,6**

	trips a day, 360 days per year		

The operation costs listed above, are used for the economical evaluation and the economical comparison with two alternative types of vessels described in Section 5.3.6.

5.3.4 Battery replacement

The cost for the replacement of the battery has not been included in the operational costs, e.g. as part of the maintenance and repair costs. Replacement of the batteries will be necessary when their performance is no longer suited for commercial ferry operation. End-of-life for this has, for the E-ferry prototype been determined to be when the overall available SoC capacity is at 80%. In principle, this decrease in battery capacity over time, could be accommodated by changing the operation schedule, including longer charging breaks, but as discussed above, this is often not a commercially viable solution.

E-ferry operator do not include costs for major overhauls or replacements of e.g. engines in their conventional vessels in their yearly budget for general expenses, for which reason the replacement of the battery system for the E-ferry prototype is also not included here. Replacing major (costly) components over a ferry's economical lifetime of 30 years or more, is however, a factor that should be considered when deciding whether to invest in an electrical ferry rather than a conventional diesel-electric ferry, hence the expected life-time and replacement costs for a new E-ferry battery pack is provided here and is included in the overall cost calculations and comparisons of Section 4.2.4 where an estimate of 500.000 Euros is also included for the conventional vessels described in the sections 4.2.3.1 and 4.2.3.2 below, with an expected replacement or major overhaul of engines for these vessels taking place after 15 years in operation.

Expected life-time of batteries was originally expected to be around 10 years, but new calculations based on the Technical Evaluation in Section 5.1.4, with known information about average energy consumption and Depth of Discharge for the E-ferry prototype suggests a life time of closer to 12 years, at t*he* current operation schedule. This based on the calculations of Table 26, below:

***Table 26*: Calculation of life time battery capacity flow E-ferry prototype battery pack**

Average Depth of Discharge (DoD)	39	%
Number of cycles down to SOH 80%	24.500	cycles
Average energy flow per cycle	1.600	kWh
Life time flow in sailing operation	39.200.000	kWh
Number of years in sailing schedule	11,74	Years

As there is no long term empirical data in existence yet, that can 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, even if it can be taken as a given that the E-ferry prototype will continue operating on the same schedule as currently. Cells have been cycled in laboratory tests and other applications and the theoretical numbers are extrapolated from this. 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 comparisons and calculations for the E-ferry prototype provided in Section 4.2.4, are based on the assumption that the whole battery pack, including BMS and other systems (e.g. fire fighting) will be replaced as a whole, after 12 years (11.74 as in table 26 above) and again in year 24, although battery life may be better for the second round of E-ferry batteries. To calculate the costs of such replacement in the future, the battery provider has provided their forecasted costs for maritime battery packs of similar size to the E-ferry prototype, at a value of 519 Euro/kWh in 2020, 360 Euro/kWh in 2025, and 211 Euro/kWh in 2030. As illustrated in Figure 42, these estimates in fact align quite well with the overall development in maritime battery systems from other suppliers, as well as with the exponential decrease in cost that applies to other packs of lithium-ion batteries, e.g. for electric cars, although EV battery packs are typically only one-third the price of maritime packs, as the latter are produced to higher standards for class approval and safety.

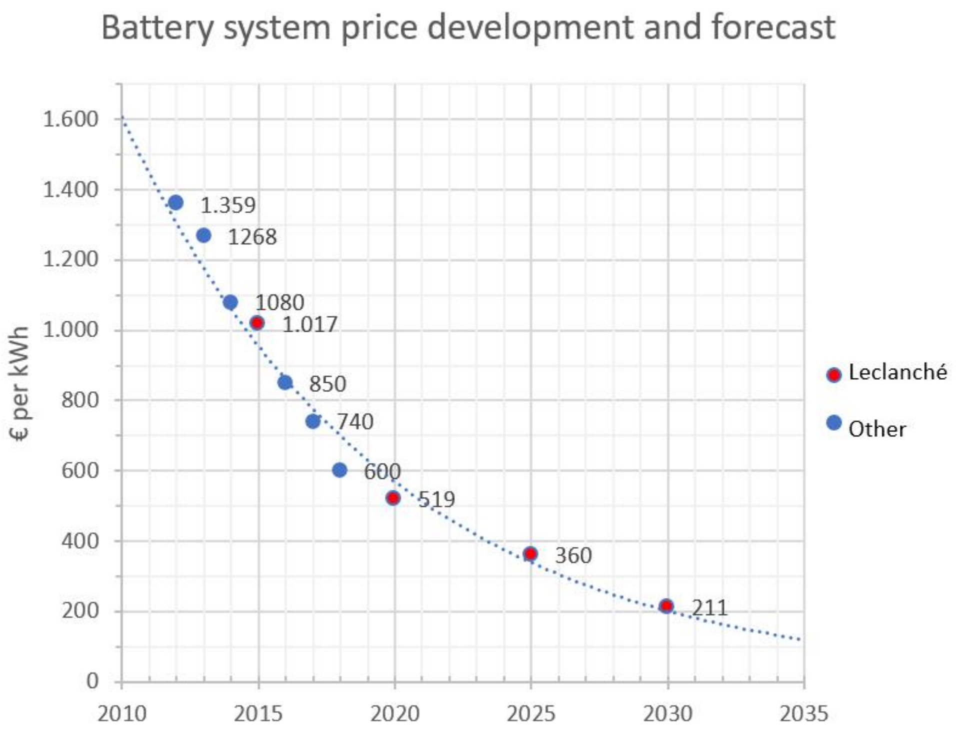

Figure 42 Compilation of battery pack price development data for maritime application gathered by Marstal Navigationsskole combined with estimates and realised prices from Leclanché.

Based on this forecast, trend and magnitude of replacement cost are provided in Table 27 below.

Table 27: Forecasted costs for 4.065 MWh battery system

Battery system price in year 2020	Battery system replacement year 2025	Battery system replacement year 2030	Battery system replacement year 2032	Battery system replacement year 2033	Battery system replacement year after 2035
2.109.718 €	1.463.400 €	857.715 €	731.700 €	569.100 €	406.500 €
519 €/kWh	*360 €/kWh*	*211 €/kWh*	*180 €/kWh*	*140 €/kWh*	*100 €/kWh*

At time of replacement of the battery modules State-Of-Health will be around 80%. Therefore, it would be obvious to assume that a so-called second-life storage application is suitable for the remainder of their lifetime. However, lifetime capacity flow of the battery cells will most likely only be 10-20% at that point in time depending on the cycling done and C-rate used in an eventual land-based storage application. Thus, there will most likely only be little resale value in the battery bank and its cells.

From the ferry owner and operator's point of view the second-life use could cover some or all of his or hers cost of decommissioning the old battery pack and instalment of the new, excluding the actual cost of the new battery pack. At present, however, there is not any mature market for the turnover of used battery cells and battery banks, though involved companies are currently looking into and testing the rebalancing of used cells from the E-ferry that was removed during testing and optimisation of battery strings during the phase 3 to 5 of the demonstration period. This potential second life project is coordinated as part of the ACOVEM project, a smaller regional Danish project focusing on speeding up the transition to electrification. Under the umbrella of the Acovem project, the related to E-ferry companies, together with other companies and the Marstal Navigational school explore the possibility of second life for E-Ferry battery cells and modules. If these experiments show a viable business case, it could very well be that we will soon have a better valuation of used battery cells from maritime applications. But for now, uncertainties are high, and the valuation of used batteries has not been a part of the overall economical evaluation in Section 4.2.4

After a possible second life in other applications, lithium-ion battery cells would still then have to be decommissioned and treated environmentally responsible. For now, typically the battery supplier has policies for the return of battery cell material or modules from customers. However, it should be said that these policies have not been put to the test yet considering the long battery life and the immaturity of the maritime battery market. The environmental impact of the rare-earth metals and partly toxic materials used in modern lithium-ion batteries is discussed further in Section 4.3.

5.3.5 Comparable vessels

To provide as fair as possible an economical evaluation of the E-ferry, the E-ferry will (in Section 4.2.4) be compared with two alternative vessels that could be put in operation on the same route as the E-ferry and deliver approximately the same service and transport performance. The two alternative vessels have been selected from an operator's perspective, with the scenario being that the operator is in need of a vessel of a particular size, speed and capacity for a particular route and has the choice either to:

(a) make a tender for a new ferry, either the fully electric E-ferry or a traditional diesel-electric vessel, or
(b) buy (or use) an older existing vessel that meets similar requirements.

Other choices that could be made by an operator is an LNG-powered vessel, a hydrogen- or fuel cell vessel, or a hybrid battery-diesel vessel. For the comparative evaluation, we have chosen not to compare these with the E-ferry; for LNG-ferries mainly because it appears that this technology is now being abandoned in the ferry industry in general, for hydrogen and fuel cell technology because this is new and unproven technology for which adequate calculations of construction and operation costs cannot be made, and hybrid-diesel vessel because this technology encompasses a huge variation in terms of battery capacity in relation to diesel tank and whether it is a plug-in charging solution or batteries are charged with a diesel generator.

Each of the specifics of the two alternatives, with which the E-ferry will be compared, both in the economical and the environmental evaluation, is described separately, below:

5.3.5.1 A new built diesel electric vessel

To find a conventional modern diesel-electric vessel to compare with the E-ferry prototype, E-ferry constructor was asked to identify a good candidate in their portfolio of recent new builds/tenders. Based on the main particulars and principal dimensions of the E-ferry prototype, the closest candidate found was the LMG-50. Table 28 lists the main particulars of the LMG-50, which can be compared with the main particulars of the E-ferry, as listed in *Table 29* below.

***Table 28*: Main Particulars of the LMG-50**

Principal dimensions	
Length, oa	64,5 m.
Length, bp	60,5 m.
Breadth, moulded	12,2 m.
Depth, moulded	5 m.
Gross tonnage	1081 t.
Draught	3,3 m.
Service speed	11 kn.
Max speed	12 kn.
Capacity and crew	
Number of cars	50
Number of trucks/trailers	5

Number of passengers	245
Number of crew	4/5
Power and propulsion	
Main engines	2x440 kW
Classification and approvals	
Flag	Denmark
Approval basis	DMA Notice D, RO Directive 2009/15EC, RO regulation (EC) 391/2009, SOLAS Chapter II-2
Classification society	DNV GL
Notations	+1A1 Car Ferry B E0 R4

The main differences between the LMG-50 and the E-ferry, aside from the fact that the first is diesel-electric and the second fully battery electric, is, firstly, that the overall dimensions of the LMG-50 are bigger than the E-ferry prototype, secondly, that the engines of the LMG-50 are somewhat smaller than the E-ferry prototype engine and thus – in combination with the size – has a somewhat lower service and max speed, and thirdly, that the LMG-50 has the class notation R4, which means that it is restricted to service areas with less than 5 nautical miles to nearest port in winter and 10 nautical miles in summer (Class notation R4).[11] Finally, the E-ferry prototype is better equipped for the transport of goods, with a deck strengthened for wheel loading (Class notation PWDK) and better equipped for navigating in periodical icy waters, with strengthened bow visor (Class notation Ice©. As the current operation area of the E-ferry on the route from Søby-Fynshav is just over 10 nautical miles between the ports, this would in principle mean that the LMG-50.1 could be restricted to sail only on the same route in the summer time. To get as close to the E-ferry specifications as possible, the LMG-50 has thus been developed further, theoretically, into a version we call LMG-50.1, so that it has an equivalent size and passenger capacity as the E-ferry prototype, as well as a similar towing resistance and propulsion speed, class notations (where possible/relevant) and so on. *Table 29* lists the main particulars of the LMG-50.1 compared to the LMG-50 on which it is modelled, as well as compared to the E-ferry prototype.

Table 29: Main comparable particulars of E-ferry prototype, LMG-50 and modified LMG-50.1

Principal dimensions			
	E-ferry	**LMG-50**	**LMG-50.1**

[11] *This could effectively mean that the LMG-50, without modfications, would only be allowed to operate on the E-ferry prototype route from Søby-Fynshav in the summer time, as the distance between ports are just over 10 nautical miles, meaning that in the winter the LMG-50 could not oblige with the restriction of less than 5 nautical miles to the nearest port.*

Length, oa	59,4 m.	64,5 m.	59,4 m.
Length, bp	57 m.	60,5 m.	57 m.
Breadth, moulded	12,8 m.	12,2 m.	12,8 m.
Depth, moulded	3,70 m.	5 m.	3,70 m.
Gross tonnage	996 t.	1081 t.	996 t.
Design, draught	2,5 m.	3,3 m.	2,5 m.
Service speed	13,5 kn.	11 kn.	13,5 kn.
Max speed	14,2 kn.	12 kn.	14,2 kn.
Capacity and crew			
	E-ferry	**LMG-50**	**LMG-50.1**
Number of cars	31	50	31
Number of trucks/trailers	5	5	5
Number of passengers	147/196	245	147/196
Number of crew	3/4	4/5	4/5
Power and propulsion			
	E-ferry	**LMG-50**	**LMG-50.1**
Main engines	2x700 kW	2x440 kW	2x700 kW
Thruster engines	2x250 kW	-	2x250 kW
Nominal battery capacity	4.3 MWh	-	-
Charging effect	4 MW	-	-
Diesel generator		?	2x1215 kW
Classification and approvals			
	E-ferry	**LMG-50**	**LMG-50.1**
Flag	Denmark	Denmark	Denmark
Approval basis	DMA Notice D, RO Directive 2009/15EC, RO regulation (EC) 391/2009, SOLAS Chapter II-2, IMO MSC.1/Circ. 1455	DMA Notice D, RO Directive 2009/15EC, RO regulation (EC) 391/2009, SOLAS Chapter II-2	DMA Notice D, RO Directive 2009/15EC, RO regulation (EC) 391/2009, SOLAS Chapter II-2
Classification society	DNV GL	DNV GL	DNV GL

Notations	1A1 Car ferry B, Battery(Power), E0, Ice©, PWDK R3	+1A1 Car Ferry B E0 R4	+1A1 Car Ferry B E0, Ice©, PWDK R3

As evident above, a number of adjustments to the LMG-50.1 have been made, to make it more realistically comparable to the E-ferry prototype. Firstly, the hull and overall dimensions have been scaled down to resemble the E-ferry prototype as much as possible. In turn, the LMG-50.1 has been equipped with strengthened bow visor and deck, to make it more suitable for operating on the E-ferry prototype route, just as relevant adjustments have been made to ensure the higher area restriction of R3, as equivalent with the E-ferry prototype. To ensure that the two vessels furthermore matches as far as possible in terms of operational speed, so they can actually cover the same route in similar time, the LMG-50.1 diesel-electric propulsion system has been upsized. This entails firstly an increase of propeller/electric engine power from 2x440 kW for the main engines, to 2x700 kW, like the E-ferry prototype. In addition, a set of two thrusters (also electric) have been added, each of 250 kW.

In terms of construction costs, the constructor estimates that the extra costs for bigger engines (and thrusters) would be neutralized by the lesser costs for steel as the hull is scaled down to resemble the E-ferry prototype; however, the upsizing of engines on the LMG-50.1 has consequences for aspects of its operation, and particular in terms of fuel consumption costs: a diesel-electric drive train is less energy-efficient than the battery-electric drive train, when measured from tank-to-propeller/battery-to-propeller respectively. This because the diesel-electric system is built up of more units, so to speak, with a diesel generator supplying an electric generator with power, and the generator then providing that power to the relevant consumers.[12] Upsizing of the LMG-50.1 propulsion system has been calculated in accordance with standard practice for dimensions of propulsion systems, as follows: The total output load for the E-ferry prototype on each of its redundant and independent systems (portside and starboard) is at peak load a total of 980 kW, from battery bank to various consumers, distributed with 700 kW to main engine, 250 kW to thruster and 30 kW to hotel load[13]. The amount of power that can be delivered from a (charged) battery bank is almost indefinite, and the loss from the battery bank to the system has been calculated at around 8%, given the E-ferry system an efficiency from battery to propeller of 0,92 (see Section 4.1.3.3).

Similar numbers for the energy-efficiency of diesel electric systems such as that on board the LMG-50.1 are provided by suppliers of diesel-electric systems, as applying from the generator, to the propeller (and other consumers). This means that to supply a total peak load of 980 kW (on each side), the E-ferry prototype two battery banks, or the LMG-50.1 two generators, should be able to supply a peak load of at least 1065 kW to its various consumers. Onboard the E-ferry prototype, this power is already directly available as electricity, but onboard the LMG-50.1, the electricity has to be generated first, by a diesel motor providing this as shaft power to the generator. The losses that occur

[12] For a fully electric system, the 'tank' could also be considered to be the charging system on-shore, and there are, as discussed in section xx indeed some losses on this side, which does affect the overall efficiency of the E-ferry prototype. As this does not relate directly to the calculation of the size of the diesel motors, however, this loss will be discussed separately in Section xx, where the economical evaluation and compariosn is provided.

[13] The total hotel load for the E-ferry is 55 kW, here shared between the two systems, though in reality, on board the E-ferry, the hotel load is always provided from one battery room, with the other serving as back-up.

in this process has been estimated (conservatively) to be about 6%, giving an energy efficiency for the diesel generator set (gen-set) of 0,94. This in effect means that the diesel motors onboard the LMG-50.1 will have to be able to supply at least 1133 kW, with the inclusion of the recommended margin for overload of such engines of 10%, the diesel motors onboard the LMG-50.1 is estimated to require a power load each of 1260 kW. For the purpose of comparison and for calculating the fuel consumption, the LMG-50.1 has thus been equipped with a set of two diesel generators of the type Wartsila 16V14 that would guarantee a maximum of 1215 kW engine output from diesel generator to transformer.

Table 30 provides the calculations for the Dimensioning of the LMG-50.1 diesel-electric propulsion system:

***Table 30*: Electrical load and required engine power on-board the LMG-50.1**

No	Item		kW power
1	Shaft power on electrical motor		700 kW
2	Shaft power on electrical thruster		250 kW
3	Electric power for ship (hotel load)		30 kW[14]
4	Total shaft power/peak load (=1.1+1.2+1.3)		980 kW
5	Efficiency transmission from generator (or battery bank)	0,92	
6	Total engine brake power demand (=4/5)		1065 kW

[14] Calculations here based on E-ferry hotel load distributed across two systems. In reality, it would be expected that a higher hotel load apply to the LMG-50.1, given that a diesel-electric system require more power consuming systems for e.g. pumps, hydraulics and cooling. For the purpose of dimensioning the system (where a 10% margin has been applied anyway), the higher hotel load is not significant, but for the overall calculation of fuel consumption below, the hotel load for LMG-50.1 has been increased.

7	Efficiency transmission from diesel engine to generator	0,94	
8	Total rated power diesel engine (=(6/7)+10% overload)		1260 kW

The total cost of constructing the LMG-50 E-ferry equivalent – as LMG.50.1 - is estimated at around 13.000.000 Euro by SSH, at today's prices, and as a delivery from SSH (or a similar Danish yard). The cost includes everything (design, drawings, hull production, outfitting, propulsion and other systems, approvals) relating to the ship itself, though of course with all land facilities, including ramps excluded. To ensure a lower manning than otherwise necessary, the LMG-50.1 has –like the E-ferry prototype –been equipped with automooring in two harbours, at an additional cost of 1.146.739,4 Euro, just as for the E-ferry, i.e. for two units, one in each harbour of current operation. The LMG-50.1 does not, of course, require the establishing costs of the on-shore electrical infrastructure for charging, nor a charger; consequently the one-time connection fee to the electricity supplier does not apply either. The total construction costs of the LMG-50.1 are listed in Table 31.

***Table 31*: LMG-50.1 construction costs**

Cost item description	Included	Cost in Euro
LMG-50.1	Design, drawings, hull production, outfitting, propulsion and other systems, approvals	13.000.000
Automooring x 2	2 on-shore mooring units, installation included, ship-side system installed and commissioned	1.146.739,4

The construction costs listed in Table 31 above are used for the economical evaluation and the economical comparison of the E-ferry prototype in Section 4.2.4 below.

Operational costs for the LMG-50.1 have been calculated based on the E-ferry prototype specifications and performance, with adjustments as relevant.

Crew/manning: Where the E-ferry prototype has a safety manning of 3 crew approved by the Danish Maritime Authority, it is highly unlikely that the LMG-50.1 would be approved with such manning, even with the E0 classification of a periodically unattended machine room. Existing practices for diesel- and diesel-electric suggests that the Danish Maritime Authority would assume that the navigational crew would neither have the competences nor the time to address problems with the diesel generators on-board the LMG-50.1, which are moreover of a power above 750 kW, which is the boundary usually referred to when determining whether a designated duty engineer is required, according to STCW code A-III/1. For that reason, it has been calculated that the LMG-50.1 (with automooring) will need (and be required to have) a safe manning crew of 4, consisting of a master, a chief officer, a chief engineer and a safety crew/catering. With a chief engineer on board at all times, the LMG-50.1 would not require the assistance of a service engineer as does the E-ferry prototype; moreover the chief engineer would in all likelihood be able to do part of the general maintenance (in addition to the maintenance of propulsion system) that on board the E-ferry is provided by a general maintenance person. Hence it has been estimated that a general maintenance person should only assist the engineer for 24 hours per month for larger maintenance related task on board the LMG-50.1.

Moreover, crew time could be reduced from 14 to 13 hours shifts per day, compared to the E-ferry prototype, as the LMG-50.1 could reduce the harbour time in Søby when compared to the relative long charging breaks needed there for the E-ferry prototype. Thus, the LMG-50.1 could cover a 5 round-trip schedule in one hour less than the E-ferry prototype, with a small reduction in working hours for crew as a result. For the LMG-50.1, the number of total operation hours per month has thus been estimated to 390 hours, in comparison with the E-ferry prototype's operation hours of 420. To cover 390 operation hours, the operation of LMG-50.1 will thus require between 2,88 and 3,00 crew shifts per month, depending on the crew category in question (see similar discussion of the difference between work time allocated to actual operation and work time allocated to other tasks, including training, vacation and illness, in Section 4.2.2.1 above). Table 32 lists the crew expenses for operating the LMG-50.1 for one month and one year, respectively, as based on the same salary averages and other calculations as those made for the E-ferry prototype.

***Table 32*: Crew costs for operating LMG-50.1**

Crew category	Average salary and employee expenses DKK/EURO	Number of crew required for one month of operation[15]	Monthly cost DKK/EURO	Yearly cost DKK/EURO	Yearly cost including pay roll fee
Master *STCW regl. II/2 as master*	69.750/ 9.362,4	3,00	209.250/ 28.087,2	2.511.000/ 337.047	2.590.975,4/ 347.781,9

[15] Note that the number of crew factor is slightly lower for the LMG-50.1 than for the E-ferry prototype, because the working shifts can be done in 13 rather than 14 hours.

Chief officer *STCW regl. II/2 as chief officer*	60.450/ 8.114,1	2.94	177.723/ 23.855,4	2.132.676/ 286.265,2	2.200.601,7/ 295.382,8
Safety crew/catering *STCW regl. V/2 paragraph 5 and table A-VI/2-1*	37.200/ 4.993	2.88	107.136/ 14.380,7	1.285.632/ 172.568,1	1.326.579,4/ 178.064,35
Chief engineer *Above STCW regl. III/3 level as usual practice*	60.450[16]/ 8.114,1	2.94	177.723/ 23.855,4	2.132.676/ 286.265,2	2.200.601,7/ 295.382,8
Able seaman /maintenance crew *STCW regl. V/2 paragraph 5 if part of safety crew*	40.300/ 5.409	0,18	7.254/ 973,7	87.048/ 11.684,3	89.820,5/ 12.056,4
Total crew cost			**679.086/** **91.152,5**	**8.149.032/** **1.093.829,8**	**8.408.578,7/** **1.128.668,3**

Energy consumption and costs for the LMG-50.1 has been based on the energy consumption known for the E-ferry prototype, with a few modifications that take into account the slightly different operational pattern of the LMG-50.1, as well as the fact that all energy consumption for the LMG-50.1 when in operation (including hotel load) will be sourced from LSMGO<0,1% marine fuel, whereas the idle power for hotel load during night time will be supplied by electricity.

As the LMG-50.1 is identical to the E-ferry prototype in terms of hull construction and weight, it has been assumed that the power required for the propulsion will be the same for the LMG-50.1. As noted in Section 4.2.2.2 above, we have calculated with a total of 1600kWh of energy from batteries on-board the E-ferry prototype, including hotel load of 55 kW during sailing and while in harbour in Fynshav. The hotel load for LMG-50.1 would be expected to be about double, due to the presence of more auxiliary and high consuming systems, such as lubrications pumps, fuel pumps and cooling. Based on data from the operator about the hotel load demand on their existing diesel vessels, we have set an estimate power load for the LMG-50.1 to 110kW. Moreover, due to the overall set-up of

[16] *Salary costs for a chief engineer is assumed to be a little higher than that of the service engineer on board the E-ferry, due to chief engineer onboard the LMG-50.1 being part of the safety crew.*

the LMG-50.1 operation, hotel load is supplied from the diesel-electric system, not just for sailing and in harbour in Fynshav, but also in harbour in Søby (where the E-ferry supplies the hotel load directly from grid through charging). On the other hand, the entire hotel load required for the LMG-50.1 when idle at night is assumed to come from electricity, just as is the case for the E-ferry prototype, as it is common practice for the operator to use on-shore power at idle time, rather than keeping the diesel engines running through the night. The number of hours of idle energy supply is slightly higher for the LMG-50.1, because the LMG-50.1 can operate the same 5 trip schedule slighter faster than the E-ferry prototype, due to the lack of needing longer charging breaks in Søby harbour (see also **Error! Reference source not found.**, where the shorter operation time has been taking into account when calculating the crew hours).

Finally, the estimated efficiency from diesel generator to transformer is slightly higher than the estimated energy efficiency from on-shore transformers to E-ferry prototype batteries, respectively a factor 0,94 and 0,92.[17] All this in turn means that the overall calculation of energy consumption for the LMG-50.1 is slightly different than that of the E-ferry prototype, though based on the same principles and assumptions. Table 33 illustrates the main differences between the two vessels in terms of specifics of energy consumption over a 24 hour period with day time operation of 5 return trips and idle night time with land power.

***Table 33*: Energy consumption per 24 hours with 5 return trips, E-ferry and LMG-50.1**

Category of consumption	E-ferry, 5 return trips	E-ferry kWh/kWh including 0,92 losses from battery to engine and 0,92 from chager to batteries	LMG-50.1, 5 return trips	LMG-50.1 kWh/kWh including 0,92 losses from genset to engine and 0,94 from diesel motor to transformer
Propulsion energy used by engines	5 return trips, electricity	8.097,8 kWh	5 return trips, marine fuel	7.925,5 kWh
Energy used for hotel load in operation	55 kW during sailing and in Fynshav harbour, electricity	597,8 kWh/	110 kW during sailing, 100 kW in Søby and Fynshav harbour, marine fuel	1.170,2 kWh

[17] The efficiency from the LMG-50.1 transformer that supply the electric engines and from the E-ferry battery systems that supply the electric engines have, as illustrated above (table xx) been estimated at same level of a factor 0,92; the 1600 kWh that is used per trip for the E-ferry prototype and also used as the basic for energy calculations for the LMG-50.1 already includes this loss in the system, for both vessels.

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	747,3 kWh	11 hours idle time/hotel load consumption from shore power, 100kW electricity	1.195,6 kWh
Total consumption, per day, electricity		9.442,9 kWh		1.195,6 kWh
Total consumption per day, marine fuel		N/A		9.095,7 kWh

To calculate the costs for the energy supplied by marine fuel, we have first to take further efficiency issues for diesel engines into consideration. 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 is running. Four stroke diesel engines typically used as generators, such as the Wärtsilä 16V14 normally performs best at around 80% of engine load, and the Specific Fuel Oil Consumption, or fuel efficiency, measured in grams of per kWh shaft energy produced will worsen when engine loads are either higher or lower than 80%. The degree of decreased efficiency is higher for low engine loads, e.g. during idling, slow steaming and less demanding manoeuvring sequences. This is illustrated in the *Figure 43* below, based on **Error! Reference source not found.**.

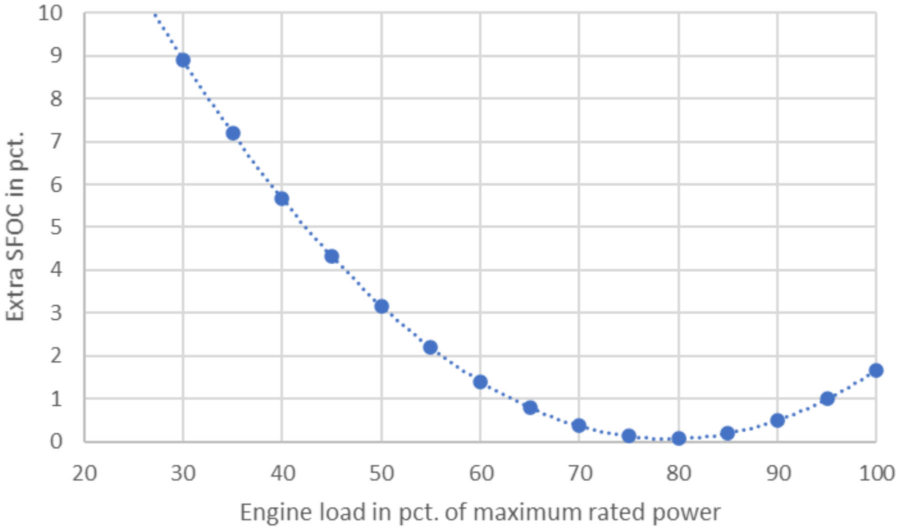

Figure 43: Variation in Specific Fuel Oil Consumption in relation to minimum SFOC at 80%. Sourced from data for 4 stroke engine approximation in Kristensen (2012)

The Wärtsilä 16V14 meets the IMO Tier III regulation for NOx emissions without the need of adding any means of mitigation such as Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR).[18] The Specific Fuel Oil Consumption of the Wartsila 16V14 Genset at 80-85% engine load is specified by the manufacturer to be 205,0 g/kWh. From this number fuel efficiencies at other engine loads can be calculated using Figure 22. The fuel efficiency given by manufacturer is, however, measured at certain ISO-defined conditions and real-world data tend to deviate from this, as illustrated in *Figure 44*, from Dedes et al.

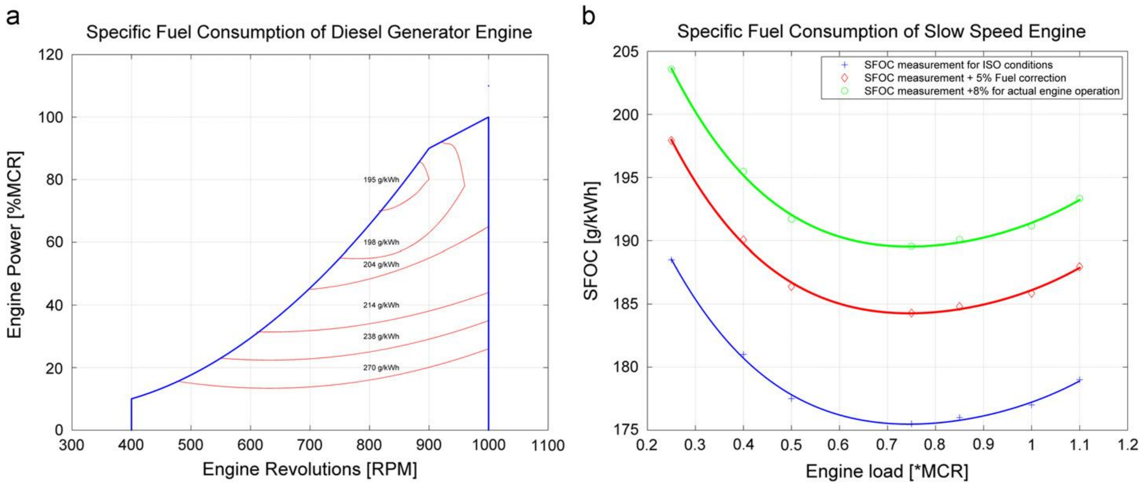

Figure 44: Specific fuel consumption graph for representative diesel generator versus engine speed and load left, examined curves of MAN 7S60MC – C8 engine (right). From Dedes et al (2011)

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[18] *Mitigation measures like EGR and SCR would add fuel penalties and extra maintenance cost.*

Many different factors may influence the Specific Fuel Oil Consumption, including sea and air inlet temperatures that may influence the performance of the engine and increase the SFOC with about 5-8% (Dedes et al, 2011), moreover the SFOC will also increase over time, as the engine is worn. According to the Aeroe-ferries, for instance, the fuel consumption on one of their traditional diesel driven vessels, M/F Ærøskøbing, has seen an increase in daily consumption from 4200 to 4800 litres, over a period of 20 years, i.e. an increase of 14,3%. As other factors (e.g. increased weight) may influence the overall use of fuel over time, a conservative estimate of 5% deviation from the Specific Fuel Oil Consumption of the Wärtsilä 16V14 engines onboard the LMG-50.1 has been added, 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 for the LMG-50.1 is thus estimated at 215,3 g/kWh, i.e. this reference point is assumed to be the consumption of marine fuel per produced kWh for the diesel motors at optimal 80% load, which for the Wärtsilä 16V14 engines onboard the LMG-50.1 equals around 972 kW each.

The power demand from propulsion and hotel load for a vessel of the LMG-50.1 type can be gagged directly from the E-ferry prototype data base and Technical evaluation as the two vessels are alike, except for the type of propulsion system implemented and the slighter higher load required from hotel load on the LMG-50.1 (see above). From there we know that the average power demand from engines, at maximum load during sea crossing – with some variation – is around 850 kW, as also illustrated in Figure 45.

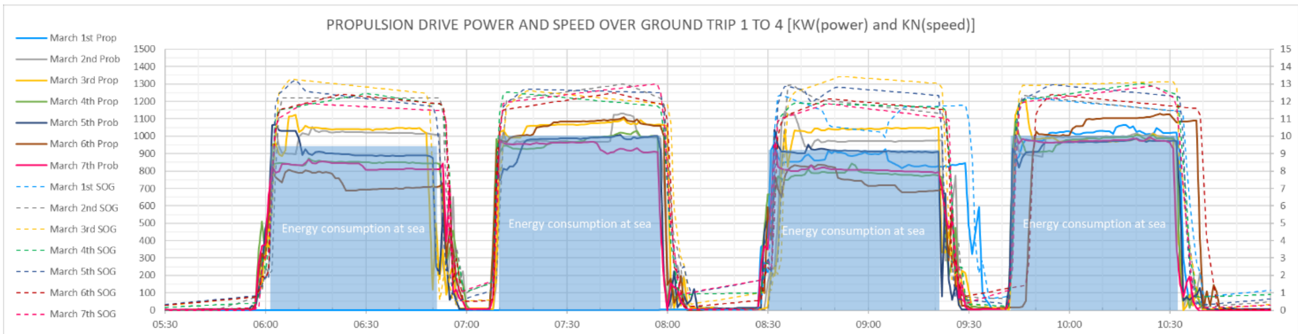


Figure 45 Data from the operation of E-ferry prototype at roundtrip 1 and 2 showing propulsion drive power and speed over ground during first week of March 2020. Approximate power use at sea speed is indicated by the blue boxes.

In addition to the power demand from propulsion while at sea, the E-ferry prototype also has a power demand of around 55 kW from the hotel switchboard, which supplies electricity to all auxiliary systems (pumps, cooling, lights, ventilation, heating as well as catering and mess equipment). On diesel-electric vessels such as the LMG-50.1, the hotel load would be expected to be somewhat higher, due to the presence of more auxiliary and high consuming systems, such as lubrications pumps, fuel pumps and cooling. Based on data from the operator on the hotel load demand on their existing diesel vessels, we have set an estimate power load for the LMG-50.1 to 110kW, with each diesel-electric system providing half of that. When taking the losses present in a diesel-electric system into account, this means that the LMG-50.1, when at sea speed (of about 12.5 knots), would have a power demand in total of 960 kW on the diesel generators, or for each diesel generator, a total of 480 kW. The total power demand when including losses is calculated in Table 34.

***Table 34*: Power load demand at sea speed, LMG-50.1**

No	Item		kW power
1	Propulsion power demand		850
2	Power load demand hotel switchboard		110
3	Total power load demand (=1+2)		960
4	Efficiency transmission from generator	0,92	
5	Efficiency transmission from diesel engine to generator	0,94	
6	Total power load demand from gensets (=(3/4)/5)		1110
7	Total power load demand per genset (=6/2)		555

As calculated in Table 34 above, the highest power load demand for each genset onboard the LMG-50.1 when the vessel is sailing at sea speed at approximately 12,5 knots, will be 555 kW, which is around half of its rated power and hence also somewhat below the level at which the diesel engines reference point for SFOC would be. Consulting *Figure 44*, with an initial SFOC of 215,3 g/KWh, at 80% of engine's power load, the SFOC at sea speed will, for the LMG-50.1 be about 3% higher, or approximately 221,8 g/Kwh. This is illustrated in **Error! Reference source not found.**, where the red dotted line indicates the power load demand for one system/genset of the LMG-50.1 at sea speed.

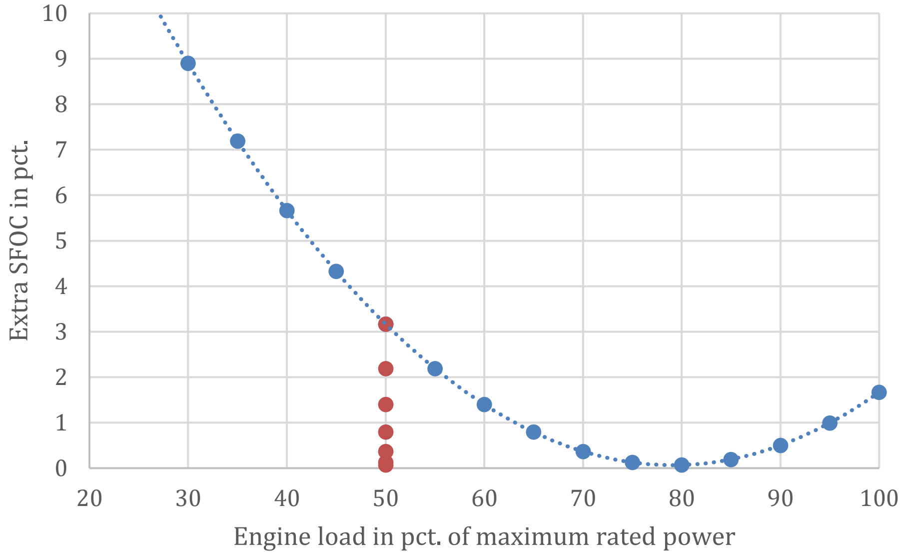


***Figure 46*: LMG-50.1 SFOC at 50% power load**

An approximate 49 minutes of each leg of a return trip is done at full sea speed and resulting high power demand. During the approximately 17 minutes of manoeuvring done by the E-ferry, the power demand is significantly lower, with a resulting higher SFOC, according to Figure *47*. Based on the E-ferry technical evaluation, we estimate an energy use of around 135,2 kWh for the 17 minutes of manoeuvring in and out of the harbours (including hotel load demand) and even less (53,2 kWh) for the brief periods where the LMG-50.1 is laying in harbours during operation hours, for loading and offloading. For both these loads, **Error! Reference source not found.** above indicates a somewhat higher SFOC than for the energy consumption at sea crossing; we have estimated the SFOC as 350 g/kWh and 250 g/kWh, respectively.

***Table 35*: SFOC for LMG-50.1 at different operation profiles, per return trip**

Energy demand	kWh	SFOC	Consumption marine fuel in kg
Sea crossing including hotel load	1668,1 kWh	221,7 g/Kwh	369,8 kg
Manoeuvring including hotel load	135,2 kWh	350 g/kWh	47,3 kg

Hotel power during port stay (in operation)	53,2 kWh	250 g/kWh	13,3 kg

The density of LSMGO<0,1% marine fuel is 0,889 g/ml, Table 36 below provides the number for daily consumption in litres and kilo grams, as well as yearly consumption in liters and metric tons.

***Table 36*: LMG-50.1 daily and yearly consumption of LSMGO<0,1% marine fuel**

Daily consumption, kg	Daily consumption, liter	Yearly consumption, liters	Yearly consumption metric ton
430,4	2421	871.560	775

To calculate the costs of the marine fuel used for operation of the LMG-50.1, we have used the same method as for calculating the electricity costs for the E-ferry (and the night supply of electricity for the LMG-50.1), by using the spot-prices for fuel over the E-ferry demonstration period from August 2019 to March 2020. As illustrated in *Figure 47* below, the development in spot prices for fuel largely followed the development in electricity prices, making this a good comparison.

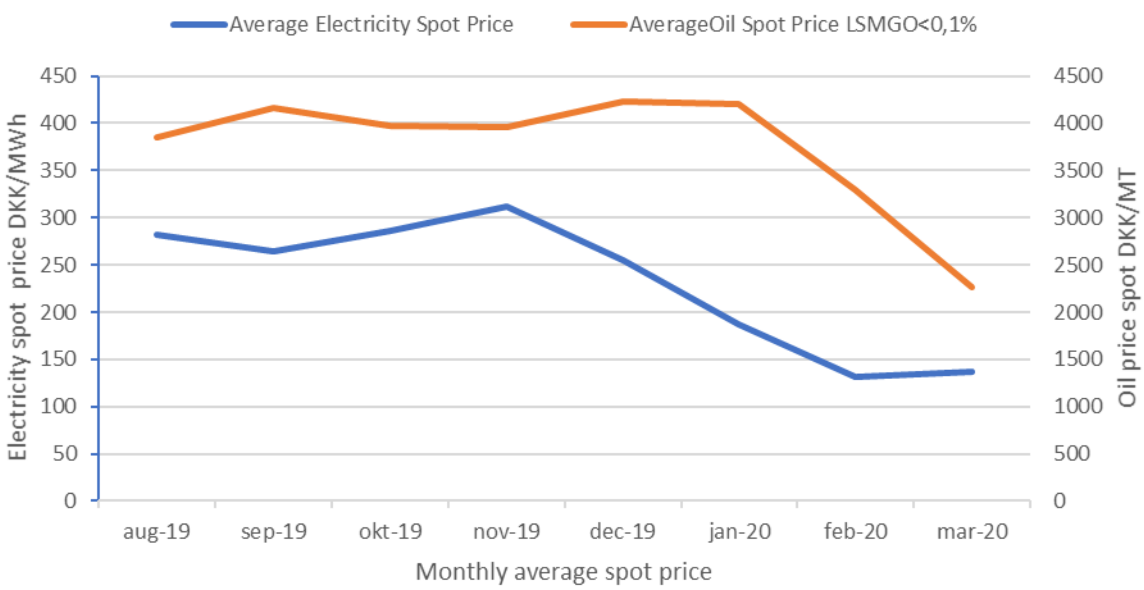


Figure 47: Development in spot prices electricity and LSMGO<0,1% marine fuel, August 2019-April 2020

For the final calculation of marine fuel costs for the LMG-50.1, the average monthly spot price of 4733 DKK/Metric Ton has been used (including partial VAT as paid by the operator). For the land supply of electricity during night time, as stated also above, the electricity spot prices of 0,5295 DKK/kWh for the E-ferry prototype has been used.[19] Table 37 provides the total cost of energy consumption for both marine fuel and electricity for the LMG-50.1.

***Table 37*: Energy costs for LMG-50.1**

Fuel type	Amount per day	Amount per month	Cost per month	Amount per year	Cost per year
Marine fuel	2,15 metric ton	64,5 metric ton	305.278,5 DKK/40.977 Euro	775 metric tons	3.668.075 DKK/492.259 Euro
Electricity	1.195,6 kWh	35.868 kWh	18.992,1 DKK/2.549,3 Euro	430.416 kWh	227.905,27 DKK/30.519,34
Total energy cost			**324.270,6 DKK/43.526,3 Euro**		**3.891.247,2 DKK/522.315,1 Euro**

Maintenance costs, including repairs, dockings and surveys of e.g. fleets, have been estimated by the operator, along with other general costs such as insurance, "other expenses" and various taxes and fees, based on usual cost practice for the operator's current fleet of diesel vessels. General costs per category are listed in Table 38, below.

***Table 38*: LMG-50.1 general costs per year**

Cost category	Costs included	Cost in DKK	Cost in Euro
Maintenance costs	Maintenance, service and repair on ship and charging system, surveys, dockings	2.720.200	365.127,52

[19] *The yearly expense of 120.675,9 DKK is about 40.000 DKK (20%) higher than what is currently budgeted for the Aeroe-ferries conventional diesel vessels and may reflect less idle hours for the other Aeroe-ferries vessels, or that some consumers are shut down during the night or are actually supplied by marine fuel or diesel in current set-up.*

Other expenses	Maintenance of on-shore installations (ramp, auto mooring etc.), various crew expenses, ticketing equipment etc. Excluding night time onshore power supply	1.300.609,7	174.578,48
Insurance	Ship	480.000	64.429,53
Total general costs		**4.500.809,7**	**604.135,5**

The total yearly costs of operating the LMG-50.1 five trips a day, every day, is listed in Table 39 below.

***Table 39*: LMG-50.1 yearly operation costs for five trips per day, every day**

Cost category	Included costs	Cost in DKK	Cost in EURO
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.	8.408.578,7	1.128.668,3
Energy consumption, operating time	Actual energy use (marine fuel) for 13 hours of operation, including hotel consumption during harbour stays, provided by diesel-electric engine	3.668.075	492.259

Energy consumption idle time	Actual energy use (electricity) for 11 hours of idle time (night), with hotel consumption, provided by electricity from land side	227.905,27	30.519,34
General costs	Estimated repair and replacement costs, dockings, surveys and service	4.500.809,7	604.135,5
Total costs	**Per year, for operation with five trips a day**	**16.805.369**	**2.255.582,1**

5.3.5.2 The existing older diesel vessel M/F Marstal

The other alternative vessel with which we will compare the E-ferry, in terms of economic and environmental impacts, is one of the operator's existing diesel driven ferries. The E-ferry comparison with this vessel is grounded in the fact that smaller operators such as the operator would, when looking to replace part of their tonnage, conceivably either use a vessel already in their fleet on a new route, or would look towards the market for used ferries, for an alternative. M/F Marstal, which is currently operated by the Aeroe-ferries on the route from Ærøskøbing to Svendborg, is one of two almost identical ferries, built for the Aeroe-ferries in 1998/1999, with an age of 20 years it could be expected to have 10-20 years of life left in it and is a such a good alternative for a new build vessel for a small operator. In terms of its particulars, the M/F Marstal is not identical to the E-ferry, however, as illustrated in the comparative Table 40 below:

***Table 40*: Main comparable particulars of E-ferry prototype and M/F Marstal**

	E-ferry	M/F Marstal
Length, oa	59,4 m.	49,9 m.
Breadth, moulded	12,8 m.	13,1 m.
Depth, moulded	3,70 m.	3,7 m.
Gross tonnage	996 t.	1617 t.

Service speed	13,5 kn.	11 kn.
Max speed	14,2 kn.	12 kn.
Number of cars	31	42
Number of passengers	147/196	250/395
Number of crew	3/4	5/6
Main engines	2x700 kW	2x1020 kW

The acquisition cost of M/F Marstal at current age of 20 years is unknown, so for determining the construction/acquisition costs for this alternative, the original building costs for the vessel has been updated to today's prices. In 1999, the M/F Marstal was constructed/acquired by the operator for around 68.000.000 DKK (on-shore facilities excluded), or approximately 9.127.517 Euro. At today's prices (factor 0,71), this equals about 96.000.000 DKK, or 12.855.657 Euro[20]. Unlike the LMG-50, which was a new build, the particulars of M/F Marstal cannot be changed, so for the comparison of this alternative with the E-ferry prototype, with either implemented on the route from Søby-Fynshav, a number of contingencies apply. Firstly, M/F Marstal would not be able to obtain the required speed of 12-13 knots that would allow it to make the crossing in 55-60 minutes. Hence a crossing time of closer to 70 minutes will have to be accepted for the M/F Marstal. Secondly, it would be unlikely (or at least very costly) to equip M/F Marstal with automooring systems, so the manning cannot be reduced from this perspective. Finally, the overall consumption of marine fuel, would, for M/F Marstal, be significantly higher than that of the LMG-50.1, because of its less energy efficient design and less energy efficient diesel engines, leading to higher fuel costs per day and year[21].

Calculations of the M/F Marstal operation costs have been based on these contingencies, as well as on the standard costs already described for the E-ferry prototype and LMG-50.1, and on information from the operator about operational costs for M/F Marstal on its existing route.

Crew/manning: M/F Marstal has a safety and manning crew of 5 when the passenger numbers are below 145 and 6 when above. For calculating the crew costs for M/F Marstal on the E-ferry prototype route, the lower number of crew has been used, as it is unlikely that more than 145 passengers will be using the route at any one time. The crew consists of a Master, a Chief Officer, a Chief Engineer, an Able Seaman and a Safety/catering Crew. Just as for the LMG-50.1, we have calculated with a daily operation time of 13 hours, due to M/F Marstal not needing to take the longer charging breaks in

[20] Note that this cost is close to what the more efficient diesel-electric LMG-50.1 would cost in today's prices. Of course, a vessel such as the M/F Marstal would not be built as is today and does not meet many of the IMO requirements.
[21] Both the extra use of fuel, as well as the way it is used, also have significant implications for Co2 and Nox emissions, but these will be discussed below.

Søby that the E-ferry prototype does. With both a Chief Engineer and an Able Seaman onboard at all times, it is assumed that not further supporting crew is required, i.e. for maintenance the calculations for crew costs are provided in Table 41 below:

***Table 41*: Crew costs for operating M/F Marstal on the E-ferry prototype route**

Crew category	Average salary and employee expenses DKK/EURO	Number of crew required for one month of operation[22]	Monthly cost DKK/EURO	Yearly cost DKK/EURO	Yearly cost including pay roll fee
Master *STCW regl. II/2 as master*	69.750/ 9.362,4	3,00	209.250/ 28.087,2	2.511.000/ 337.047	2.590.975,4/ 347.781,9
Chief officer *STCW regl. II/2 as chief officer*	60.450/ 8.114,1	2.94	177.723/ 23.855,4	2.132.676/ 286.265,2	2.200.601,7/ 295.382,8
Chief engineer *Above STCW regl. III/3 level as usual practice*	60.450[23]/ 8.114,1	2.94	177.723/ 23.855,4	2.132.676/ 286.265,2	2.200.601,7/ 295.382,8
Safety crew/catering *STCW regl. V/2 paragraph 5 and table A-VI/2-1*	37.200/ 4.993	2.88	107.136/ 14.380,7	1.285.632/ 172.568,1	1.326.579,4/ 178.064,35
Able seaman /maintenance crew *STCW regl. V/2 paragraph 5 if part of safety crew*	40.300/ 5.409	2,88	116.064/ 15.579,1	1.392.768 186.948,7	1.437.127,7/ 192.903

[22] Note that the number of crew factor is slightly lower for the LMG-50.1 than for the E-ferry prototype, because the working shifts can be done in 13 rather than 14 hours.
[23] Salary costs for a chief engineer is assumed to be a little higher than that of the service engineer on board the E-ferry, due to chief engineer onboard M/F Marstal being part of the safety crew and because of local employment agreements.

Total crew cost			**787.896/ 105.757,9**	**9.454.752/ 1.269.094,2**	**9.755.885,9/ 1.309.514,9**

Energy consumption and costs for the M/F Marstal has been calculated similarly to that of the LMG-50.1, i.e. based on the energy consumption known for the E-ferry prototype, with a few modifications that take into account the slightly different operational pattern of M/F Marstal and in particular the less energy efficient hull and engines of M/F Marstal as compared to LMG-50.1. To obtain the maximum required speed, the energy demand for M/F Marstal's genset will thus, according to calculations, be 1787 kW, rather than the 900 kW required for the LMG-50.1 (both including losses). Similarly, the hotel load of M/F Marstal is higher than that of LMG-50.1, at 130 kW. On the other hand, M/F Marstal will – due to higher load requirement – for most of its time in operation (with the exception mainly of hotel load consumption during port stays) be much closer to its ideal SFOC load. Table 42 lists the overall consumption of M/F Marstal per return trip on the Søby-Fynshav route, in KWh, the SFOC calculated for each type of consumption, as well as the overall consumption in kg of marine fuel.

***Table 42*: Consumption of marine fuel for M/F Marstal on a return trip from Søby-Fynshav**

Consumption category	Energy in kWh	SFOC at required load	Consumption marine fuel LSMGO<0,1 %
Propulsion sea leg	2.018,8 kWh	179 g/kWh	522,5 kg
Hotel load during sea leg	254,8 kWh	179 g/kWh	45,6 kg
Maneuvering (including hotel load during	171,8 kWh	320 g/kWh	55 kg
Hotel load during port stay	65 kWh	550 g/kWh	35,8 kg

Total consumption one return trip			658,9 kg

Table 43 provides the final calculation of all energy costs for M/F Marstal, when sailing a 5-trip schedule in 13 hours, on the E-ferry prototype route between Søby and Fynshav. Included here is also the shore power supplied as electricity during the 11 idle (night) hours, with an expected hotel load of 130 kW.

***Table 43*: Energy costs for M/F Marstal**

Fuel type	Amount per day	Amount per month	Cost per month	Amount per year	Cost per year
Marine fuel	3,3 metric ton	98,8 metric ton	462.581,6 DKK/62.091,5 Euro	1186 metric tons	5.552.852 DKK/745.349,3 Euro
Electricity	1430 kWh	42.900 kWh	22.737 DKK/3.052Euro	430.416 kWh	272.844 DKK/36.623,4 Euro
Total energy cost			**786.852,2 DKK/105.617,73Euro**		**5.825.696 DKK/781.972,6 Euro**

Maintenance costs, including repairs, dockings and surveys of M/F Marstal is based directly on the Aeroe-ferries budget for same, as listed in Table 44, below:

***Table 44*: M/F Marstal general costs per year**

Cost category	Costs included	Cost in DKK	Cost in Euro
Maintenance costs	Maintenance, service and repair on ship and charging system, surveys, dockings	2.720.200	365.127,52
Other expenses	Maintenance of on-shore installations (ramp, auto mooring etc.), various crew expenses, ticketing equipment	1.255.671	168.546,4

	etc. Excluding night time onshore power supply		
Insurance	Ship	480.000	64.429,53
Total general costs		**4.455.871**	**598.103,5**

The total yearly costs of operating M/F Marstal five trips a day, every day, on the E-ferry prototype route, is listed in Table 45 below.

***Table 45*: M/F Marstal yearly operation costs for five trips per day, every day**

Cost category	Included costs	Cost in DKK	Cost in EURO
Operating crew costs	5 crew, as approved, including two navigators, a chief engineer, an able seaman and a catering crew with safety papers. 13 hours shift per day.	9.755.885,9	1.309.514,9
Energy consumption, operating time	Actual energy use (marine fuel) for 13 hours of operation, including hotel consumption during harbour stays, provided by diesel genset engine	5.552.852	745.349,3
Energy consumption idle time	Actual energy use (electricity) for 11 hours of idle time (night), with hotel consumption, provided by electricity from land side	272.844	36.623,4
General costs	Estimated repair and replacement costs, dockings, surveys and service	4.455.871	598.103,5
Total costs	**Per year, for operation with five trips a day**	**20.037.423**	**2.689.587**

5.3.6 Overall cost analysis

In the previous sections, information about the construction and operational costs of Ellen has been provided. Moreover, and in order to examine the impact of the E-Ferry from an economical and investment perspective, the construction cost of a newbuild E-ferry series no. 3 vessel without the prototype development cost and with present battery system prices (year 2020) was also found. Two different conventional ferries have been selected against which E- and the E-ferry series no.3 will be compared and similar details have been calculated and provided for these two vessels:

- The LMG-50.1 a new built diesel – electric vessel and
- An existing, older vessel, the M/F Marstal

The construction costs of these four ferries are depicted in Table 46, below:

***Table 46*: Summary of construction costs, 4 comparable vessels**

Vessel	Cost of ferry (€)	Cost of shore charging system (€)	Cost excluding development costs (€)	Cost including auto mooring for 2 harbors (€)
E-ferry prototype	16.661.848	2.451.660	18.492.945	**19.639.684**
E-ferry series no.3	13.250.432	2.344.810[24]	n/a	**16.741.981**
LMG-50.1	13.000.000	n/a	n/a	**14.146.739**
M/F Marstal	**12.855.657**	n/a	n/a	n/a

In order to make a fair comparison of the E-ferry prototype and E-ferry series no.3 against the other two vessels, we use the cost that do not include development costs, but does include cost for automooring for two harbors. Similarly, for LMG-50.1 we use the price that includes costs for automooring in two harbors. The existing ferry M/F Marstal is moored manually and therefore does not include automooring costs. The construction costs that will be used for each of the vessels have been highlighted in red.

Following the same rationale, Table 47 below summarizes the operational costs for each vessel, as calculated above. All the operational costs include relevant taxes and are presented on a yearly basis. Given that the E-ferry operates in Denmark, the tax regulations that have been taken into consideration are the ones that are imposed in the specific country. In general, Denmark is a country with a high 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

[24] Shore charging system reduced with a factor 0,9 compared to E-ferry prototype due to economy of scale. One-time connection fee not reduce, as this is defined by power demand, which is the same for both vessels.

friendly solutions in general (the latter). The comparison is however considered fair, at least regarding taxes, as there is a global trend towards favorable taxation of solutions related to renewable energy sources.

***Table 47*: Summary of operational costs for the four vessels**

Vessel	Total costs/year (5 trips/day - 360 days/year) (€)
E-ferry prototype	1.713.669,6
E-ferry series no. 3	1.713.669,6
LMG-50.1	2.255.582,1
M/F Marstal	2.689.587

As anticipated, the conventional ferry types have lower construction costs than the E-ferry prototype. More specifically, investment cost of LMG-50.1 is **28% lower** than for the E-ferry prototype including charging station and automooring. If the investment cost of the Danish-build 20-year old existing diesel ferry M/F Marstal is adjusted for Danish price index changes it would be **35%** lower. This is something that was of course anticipated as the technology implemented on E-ferry is by far more advanced and up-to-date and have still not matured fully therefore more expensive. However, as also indicated in Table 47 above, construction of a new E-ferry number 3 in a series would, with today's battery prices and economy of scale, be significantly reduced in price compared to the E-ferry prototype. and the cost of LMG-50.1 would thus be only **16%** lower than the E-ferry series no.3, when including investment cost for the charging station/electrical infrastructure. In other words, as battery prices decrease, the main economical difference between a fully electric vessel and a conventional vessel, will be the extra technology and connection fees required to access the power from shore side.

In terms of operational costs, both the E-ferry prototype and the E-ferry series no 3, by comparison, fares significantly better than both the comparable vessels, with 24% savings compared to the LMG-50.1 and 36% compared to the existing M/F Marstal. As these are yearly savings, as opposed to the construction costs that are a one-off investment, the savings on operational costs will eventually mean that the E-ferry prototype and the E-ferry series 3 will eventually break even. Figure 48, below, indicates that the investment of the E-ferry prototype would pay off within 7-10 years compared to LMG-50.1 and M/F Marstal respectively, whereas the E-ferry series no 3 investment would pay off within 4-5 years. For these calculations, the economical lifespan of the vessels have been assumed to be 30 years, which is normal practice for ferry operators. Cost for replacing battery system on board the E-ferry prototype and the E-ferry series no. 3 have been added in both year 12 and year 24 (though lifetime of second battery system is likely to be longer, as discussed above). A one-time (through the 30 year lifespan) replacement or major overhaul/upgrade of the equivalent diesel engines and generator has been added for the two conventional vessels, for year 15 and at a cost of 500.000 Euro, again in accordance with practice. Battery prices for year 12 and 24 are based on the forecasting found in Section 4.2.1 (Table 27). Operational costs are assumed to be stable in the full lifespan of the vessel.

Figure 48 Total investment cost and operational cost added over a 30-year life span for each of the four vessels. Simple break-even or cost parity is illustrated by the red arrows.

The simple break-even method shows cost parity between the E-ferry series no.3 and the new diesel electric LMG50.1 after **5 years** and the existing diesel ferry in operation M/F Marstal after only **4 years** based on the calculated investment and operational cost presented above. For the significantly more expensive E-ferry prototype cost parity to the new diesel-electric LMG50.1 is shown after close to **10 years** and for the existing diesel ferry M/F Marstal after close to **7 years**.

From an operator or investor's point of view the simple break-even or cost parity method above does not reflect the change in value of money (inflation) and distribution of cost in time for such a long time asset and investment as a ferry with charging infrastructure. Therefore, a second method has been applied also using an internal discount rate of 4% typically recommended by the Danish Ministry of Transport (2015) for transport modelling and socio-economic effects. This is illustrated in Figure 49, below.

In this second (present value) method future costs are discounted back to present value with an annual discount rate of 4% by dividing calculated added annual cost with $(1+0,04)^y$ where y is the year after construction. All costs are then accumulated, as above, to find cost parity. In the present value method, future savings or future investments are weighted lower than present or short-term savings and costs. This therefore impact the time of cost parity, due to the higher investment cost of the E-ferry prototype and E-ferry series no.3, especially with the extra cost associated with the charging system and electrical infrastructure. By comparison, both the future costs of battery packs in the E-ferries and engine replacement in the conventional ferries are less emphasized with this calculation method.

Figure 49 Present value method of finding cost parity between the four vessels using a recommended discount rate of 4% p.a.

The present value method shows cost parity between the E-ferry series no.3 and the new diesel electric LMG50.1 after **5,2 years** and the existing diesel ferry in operation M/F Marstal after **4,3 years** based on the discount rate of 4%, delaying the time of cost parity a few month compared to the first and simple break-even method. For the more expensive E-ferry prototype cost parity to the new diesel-electric LMG50.1 has moved significantly and is now first after close to **15 years** and for the existing diesel ferry M/F Marstal it is now after **8 years**, one year later than the simple method. As mentioned, the present value method will favor higher cash flows in the beginning of the lifespan.

For both E-ferries, one of the most significant impacts on the cost parity is the higher investment cost up-front, both for the battery systems and the electrical infrastructure/charging system on shore. As indicated above, (section 4.2.2.4, Table 25) battery prices for maritime applications are forecasted to decrease significantly over the next years, this eliminating a substantial amount of up-front costs for electrical ferries, as already exemplified by the cost difference between the E-ferry prototype and the E-ferry series no. 3, with today's battery prices. Another promising area at which to consider reducing up-front costs (as well as further reducing energy costs), would be, as also discussed in sections 4.2.1 and 4.2.2, to consider an alternative ownership structure of the charging transformer station, than that which has been used for the E-ferry prototype. Table 48 summarizes the potential savings on the investment costs of E-ferry series no 3, with the alternative ownership structure in place.

***Table 48*: Summary of construction costs with ownership of 10kVA grid transformer for the E-ferry series no.3 vessel (B-high customer), 4 comparable vessels**

Vessel	Cost of ferry (€)	Cost of shore charging system (€)	Cost excluding development costs (€)	Cost including auto mooring for 2 harbors (€)
E-ferry prototype	16.661.848	2.451.660	18.492.945	**19.639.684**
E-ferry series no.3	13.250.432	1.857.575	n/a	**16.254.746**
LMG-50.1	13.000.000	n/a	n/a	**14.146.739**
M/F Marstal	**12.855.657**	n/a	n/a	n/a

With alternative ownership of transformer system, the cost of the shore charging system would be reduced by 24%, as the one-time connection fee is substituted by the investment cost of the high voltage cabling and transformers. Change of ownership would also – 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 energy costs of 12%, including VAT. The reduction in energy costs for E-ferry series no 3, when operating on the same schedule of five trips per day as that earlier evaluated, but paying the B-high tariff instead, is listed in Table 49, below.

***Table 49*: Summary of operational costs with ownership of 10kVA grid transformer for the E-ferry series no.3 vessel (B-high customer) for the four vessels**

Vessel	Total costs/year (5 trips/day - 360 days/year) (€)
E-ferry prototype	1.713.669,6[25]
E-ferry series no. 3	1.670.645,0
LMG-50.1	2.255.582,1
M/F Marstal	2.689.587

[25] From 2022 and beyond the Danish PSO-tariff is phased out and the operational cost for the E-ferry prototype will be reduced to 1.700.320,7 € per year hereafter. This effect has already been accounted for in the E-ferry series no.3 in this table for future estimates.

Based on the updated/adjusted cost calculations for the E-ferry series no.3 with ownership of 10kV grid transformer the same two methods as above have been applied to the four vessels investment and operational cost resulting in Figure 50 and Figure 51 below.

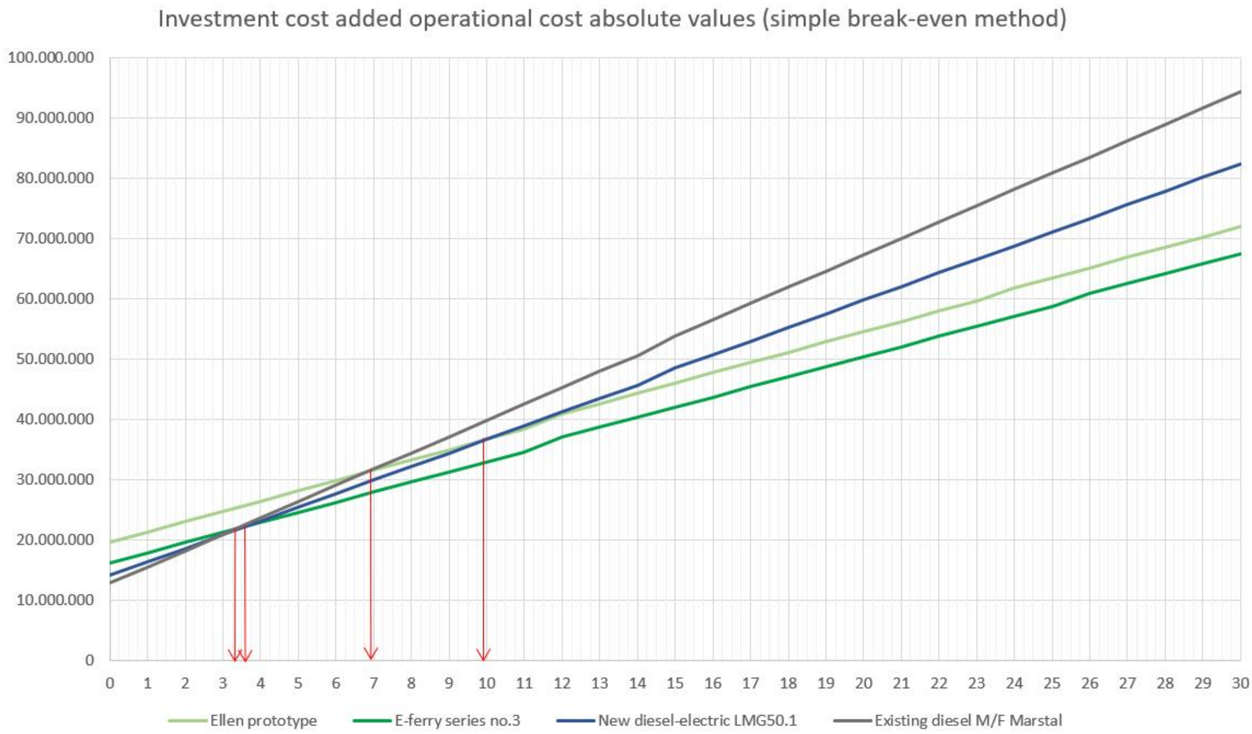


Figure 50: Total investment cost including transformer and high voltage infrastructure and operational cost added over a 30-year life span for each of the four vessels. Simple break-even or cost parity is illustrated by the red arrows.

The simple break-even method now shows cost parity between the E-ferry series no.3 and the new diesel electric LMG50.1 after only **3,6 years** and the existing diesel ferry in operation M/F Marstal after only **3,3 years** moving break-even forward with 9-14 month compared with the current ownership structure for the transformer system and electrical infrastructure. Though the E-ferry prototype has retained the old ownership structure, cost parity has also moved a little for the prototype, with 2 months, because PSO-tariffs have been phased out from 2022 and beyond for this calculation scenario.

In the second (present value) method, an annual discount rate of 4% - as above - has been used on all future cost to reflect better the impact of cost timing. Again, this will normally lead to longer time to break-even because investment is placed in the beginning of the lifespan of the vessel.

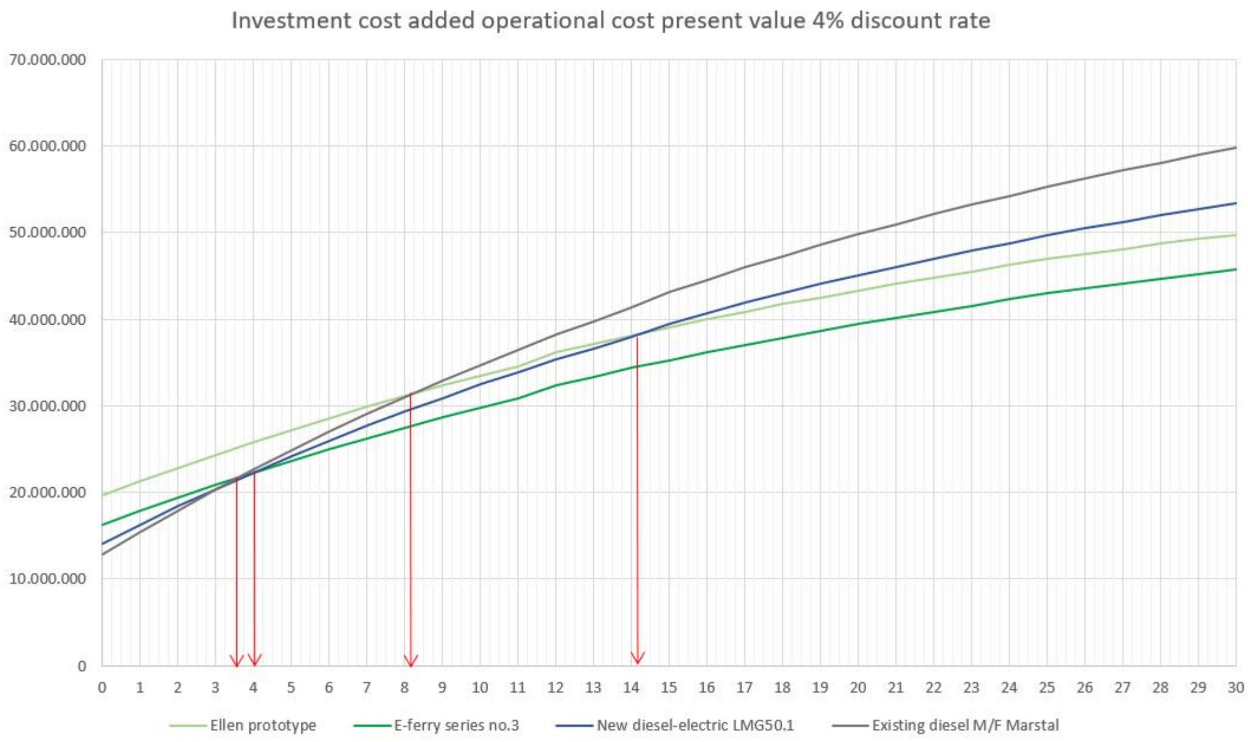


Figure 51: Total investment cost including transformer and high voltage infrastructure and operational cost added over a 30-year life span for each of the four vessels. Simple break-even or cost parity is illustrated by the red arrows.

The present value method now shows cost parity between the E-ferry series no.3 and the new diesel electric LMG50.1 after **only 4 years** and the existing diesel ferry in operation M/F Marstal after **3.6 years** based on the discount rate of 4%. This again, is an improvement of 9-14 months. Thus it can be concluded that the alternative strategy of taking ownership of the high voltage infrastructure and becoming a B-high customer has indeed an significant impact to cost parity and breakeven times.

From the graphs in Figure 49 and Figure 51 it can also be concluded that present value of the 30-year lifetime savings between E-ferry series no.3 and LMG50.1, using a discount rate of 4%, will improve by 1.231.295 € (from 6.437.557 € to 7.668.852 €), fully covering the risk of the extra investment.

The calculations that have taken place in the specific section have been done only from the financial point of view. The environmental and social benefits that will be analyzed in the sections that follow have not been included. These environmental or social benefits that will naturally accrue from the use of an electric ferry will certainly lead to more benefits, some of them financial as well. For example, higher speed will lead to higher frequency of trips, higher transport quality and therefore higher number of passengers and hence higher income for the operator.

On the other hand, the environmental benefits of operating an electric ferry will be more and more prominent, putting pressure on governments to lower taxes on the use of this kind of technology or environmental tax on fossil fueled vessels. If e.g. CO_2 emissions from the conventional peer ferries (LMG-50.1 and M/F Marstal) were to be added, at the present price of CO_2 quotas traded within the EU Emission Trading System (ETS), at around 20 € per ton per CO_2-equivalent, it would add another 135.136,7 € annually to the operational cost of LMG50.1 and 498.067,6 € annually to the cost of M/F Marstal in the operational scheme described and calculated above. These are significant extra potential costs of respectively 6,0% and 18,5% that could be imposed on conventional ferry operation in the way forward to meet the EU and national climate goals.

Moreover, incentives will certainly be provided to operators, in order for them to purchase electric ferries. Following, increase in the demand for electric ferries will, based on the economies of scale, further decrease the construction costs, making this choice more and more financially beneficial.

To summarize the findings of this economic evaluation, the construction costs of the E-ferry protype and its charging station are currently more expensive than the two ferries against which she was compared. The operational costs of E-ferries however are significantly lower, and both construction and operational costs could be improved further by implementing the alternative customer strategy for electricity purchase, at least in a Danish context. The calculations depicted above, clearly show that at an early point, both the E-ferry prototype and its future sister vessels, are more cost-effective than LMG-50.1 and M/F Marstal, when taking a life-time expectancy of 30 years for ferries of this type into account. Should the further benefits of the E-ferry be taken into consideration (social and environmental) and be "translated" into costs, then she is also by far the most effective solution.

5.3.7 KPI – economical evaluation

The main indicators on which the E-ferry economical evaluation has been based, and which the above analysis and discussion have evaluated, are as follows:

Table 50: Indicators to be assessed for the energy cost calculation

	Indicator	Unit	Compared to LMG-50.1	Compared to M/F Marstal	Comments
1	Reduction in energy cost	€/MWh	53,7%	69,1%	-----
2	Reduction in fuel cost per trip	Euros	57,4%	70,1%	For this calculation tables including fuels costs have been taken into consideration. The fuel cost for peers take into consideration both marine fuel and electricity from land at night.
3	Increase in the Public Service Obligation (PSO) cost	Euros	The Public Service Obligation cost on electricity is being phased out and will disappear fully in 2022 in Denmark		

4	Decrease in taxation	Euros/year	Denmark, Sweden and Germany have introduced tax exemption in 2014 for electricity to be used onboard ships in general as fossil fuel bunker was already exempted from tax. Norway has a similar exemption. The electricity does not need to be based on renewable sources but grid mix of renewables is high in these countries already.
5	Decrease in CO_2 quotas	€/MWh	Several policies are expected to be implemented in the coming years imposing decrease in CO_2 quotas for ferries using renewable energy sources. This is not clear yet.
6	Increase in the energy cost for heating and air conditioning	€/trip	There was no increase in the energy cost for heating and air conditioning. Hotel power seems to be lower than for a conventional fossil fuel ferry, due to the higher energy efficiency of battery operation.
7	VAT exemption (if any)	€/year	Among the taxes from which electric ferries are expected to be exempted is the VAT. This is already the case in Norway. For Denmark VAT is not to be paid for passenger transport. However, the battery ferry will pay VAT according to the split between cargo and passenger income. It is right now being discussed in Denmark if electricity for ferries should be exempted from VAT as well. Again, this is not clear yet and varies from country to country.

Table 51: Indicators to be assessed for the operating cost evaluation

	Indicator	Unit	Compared to LMG-50.1	Compared to M/F Marstal	Comments
1	Necessary crew	Number of people	For Ellen: 3-4 For LMG-50.1: 4-5	For Ellen: 3-4 For Marstal : 5-6	Slight improvement compared to both ferries
2	Total manning costs	€/year	12,1% (decrease)	30,1% (decrease)	The Chief Engineer is not mandatory for Ellen. A Service Engineer will take care of running maintenance.

3	Maintenance costs	€/year	37,4% (decrease)	37,4%(decrease)	Based on budgets, as demonstration period is too short to conclude. Costs could be lower.
4	Repairs' costs	€/year	Have been included in the above indicator		
5	Costs for consumables (ex. Lubricating oil)	€/year	10,8% (decrease)	6,5 % (decrease)	Total decrease based on all Other expenses, likely to be much higher for e.g. lubricating oil
6	Maintenance costs for shore installations	€/year	9,75% (decrease)	6,5% (decrease)	
7	Cost for shore based ship service	€/year	N/A	N/A	Not available from operator
8	Dry docking cost (expected to take place every two years)	€/year	N/A	N/A	Not yet determined
9	Classification and safety equipment's costs	€/year	N/A	N/A	Not yet determined, but unlikely that this will differ for the three vessels
10	Hull and machinery insurance costs	€/year	N/A	18,9% (increase)	E-ferry insurance includes charging system and transformerhouse
11	Protection and indemnity insurance costs	€/year	N/A	18,9% (increase)	Included in above

5.4 Environmental evaluation

This section presents the overall environmental evaluation of the E-ferry prototype. During the project period, a Life Cycle Analysis was also conducted which clearly concluded that the difference between a fully electric propulsion system on the one hand, and, respectively a conventional diesel vessel (like M/F Marstal) or a diesel-electric vessel (like LMG 50.1) on the other hand is significant when considering the overall environmental impact over a ferry's lifetime, independently of whether the E-ferry prototype would be operating with electricity from the Danish mixed grid (see below) or with green energy sourced only from wind energy. This also when taking into consideration the potential scarcity of some mineral resources (Cobolt, Nickel and Mangan in particular) used for the E-ferry G/NMC batteries, as well as the resources employed to produce the batteries. The overall conclusion of the LCA is illustrated in Figure 52 below.

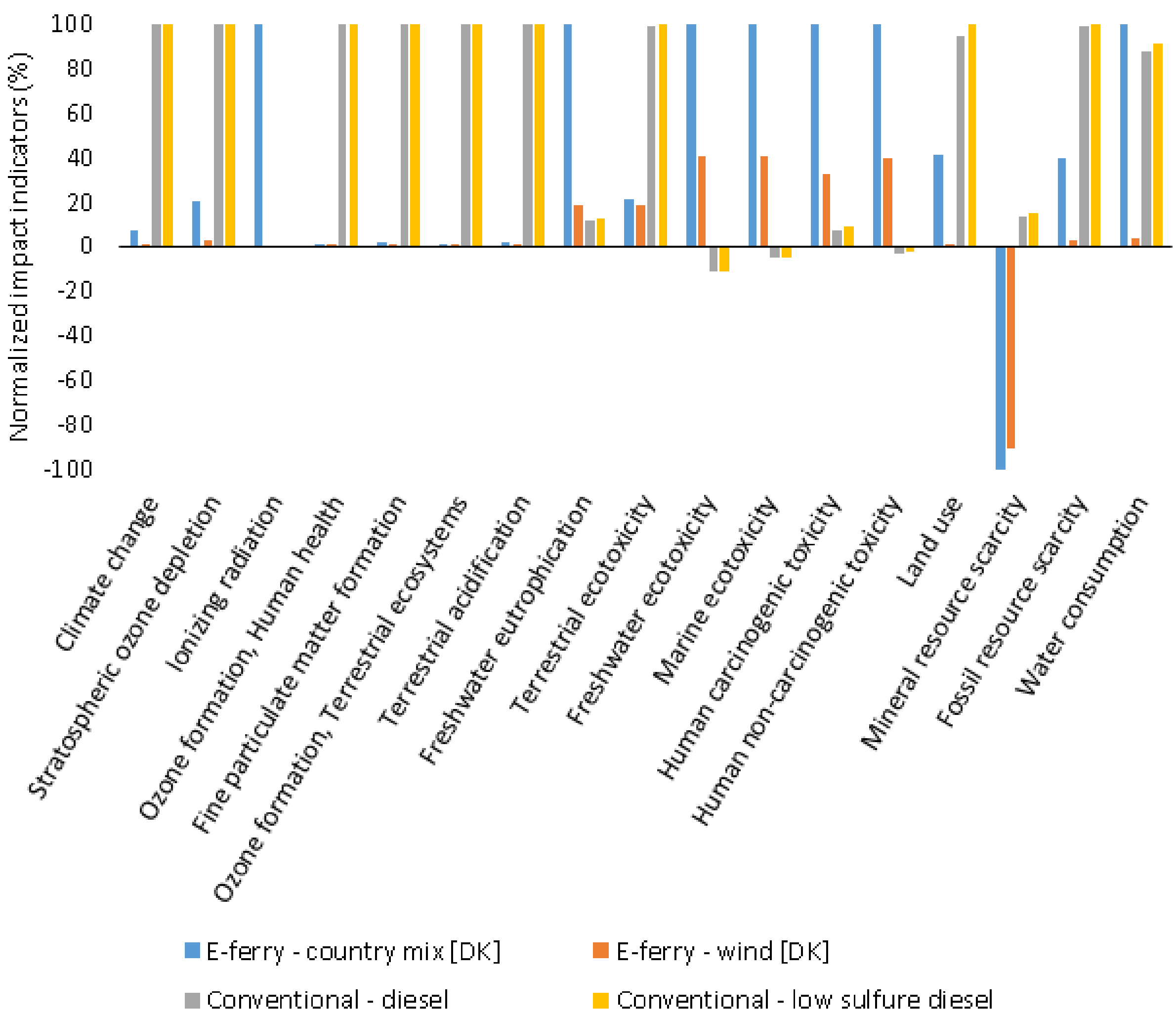


Figure 52: Conclusion from Life Cycle analysis of three different vessels, DTU

The LCA study conducted, was based on a cradle-to-grave approach, taking all stages of the process into account, with the exception of material extraction. Figure 53 illustrates the scope of the study, with the light blue colour indications aspects not within the scope.

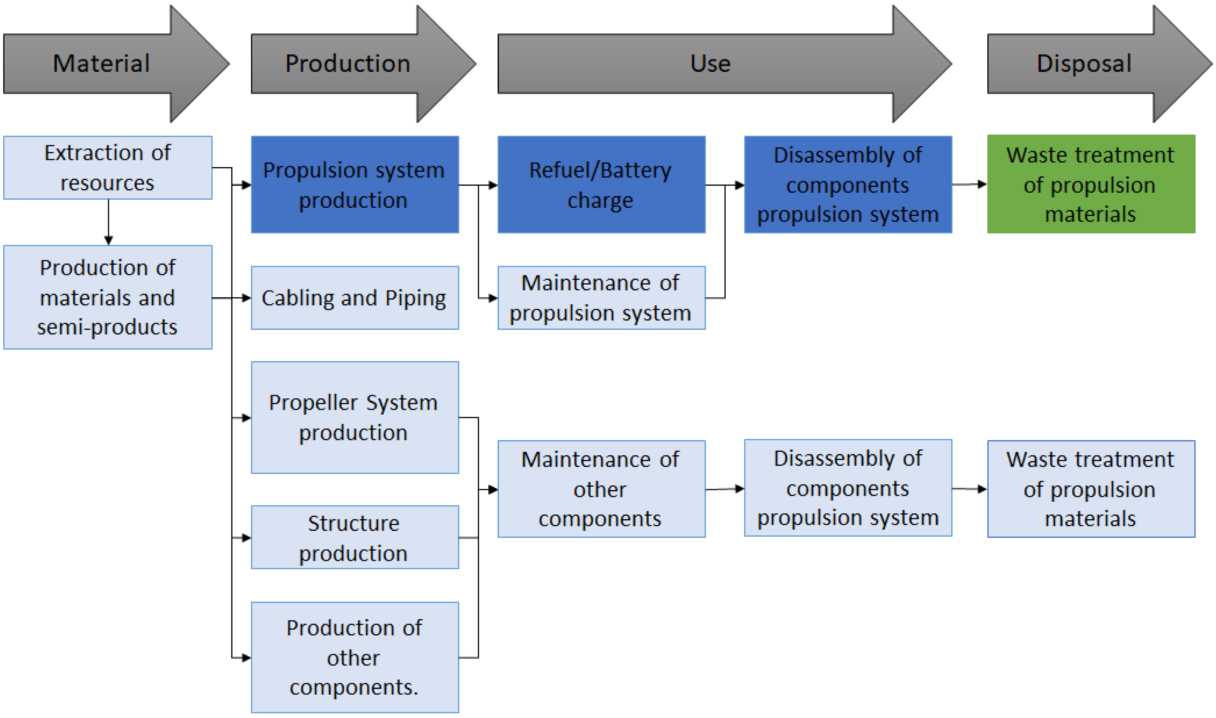


Figure 53: Flow diagram of the boundaries of the studied system from the LCA

17 environmental impact categories were investigated, based on a comparative inventory analysis of the propulsion system of the E-ferry and its peers, and with the use of material databases from Ecoinvent. It was highlighted that in many categories, basically non-toxicity impact categories, the E-Ferry prototype perform better than the conventional ferries. Furthermore, in most of the categories, the E-Ferry prototype, whether supplied with an electricity mix from the Danish grid or with electricity coming exclusively from wind energy, seems to perform better compared to its alternatives, thus, as it was expected, this seems to be the preferable option from an environmental perspective.

This conclusion, however, might change if toxicity impact categories (where the E-Ferry performs worse) are given a higher weighing than the rest of the impact categories. According to the LCA, however, the primary environmental impact comes from the use stage, whereas impacts from the production and disposal stage are less significant. As the LCA does not as such consider the material extraction stage, it is not clear how the E-ferry prototype would fare on this part of the process from cradle-to-grave. The methodology applied in the LCA does, however, address the potentially critical issue of material extraction and use of rare-earth materials and toxic materials (e.g. Cobalt) that are used in Lithium-ion batteries. Three sets of batteries are thus investigated for the LCA analysis' 30-year period, where it is assumed that a total of 104 tons of cell material is 100% recycled using the existing process labelled "Used Li-ion battery {GLO}" for this in the Ecoinvent database. It should be noted that Life Cycle Inventory data for Material and Disposal have been extrapolated from year 2005 to 2016, the uncertainty has been adjusted accordingly. The global average recycling processes represents two different technologies involved in the treatment of Li-On batteries for the disposal part.

In reality the use of e.g. rare-earth materials and toxic materials like Cobalt in Lithium-ion batteries has been reduced significantly since 2005 from where the database values were extrapolated. Furthermore, future changes to battery chemistry will most likely change the composition of cell materials for the two third of battery volume remaining to be produced in twelve and twenty-four years for the replacement of the first battery pack. Finally, second life use of replaced battery packs has not been subtracted at the use stage of the LCA analysis for the E-ferry. Therefore, impact assessments of especially toxicity could be somewhat exaggerated.

For the climate impact the LCA study is on-par with other Norwegian maritime studies, as well as with our technical and environmental evaluation of the E-ferry in operation (see below). The Norwegian study from 2016 thus shows that the climate impact of battery production is repaid much faster than for land-based Electrical Vehicles, this being due to high usage time of the battery system in a ferry, 60-70% of the time, compared to other EV's, which will typically be parked for 90% to 95% of the time on average. Even for electrical vehicles more generally, there is a high discrepancy between different studies, in terms of the emission factors from battery production (kilos of CO_2-equivalent emitted for the production per kWh battery cell), providing numbers that ranged from 50 to several hundreds of kilos. Some of this research is, however, based on very old inventory databases, from a time when battery price and energy use for battery production were both many times higher than at current time, i.e. before economies of scale and innovation in the production process gained momentum. The emission numbers that suggest several hundreds of kilos of CO_2 per kWh cell produced, does not, for instance, relate in any meaningful way to current battery prices of 100-200 Euros per kWh for batteries e.g. for shore-based applications. A more realistic number for the present stage of technology would thus be estimated at between 50-100 kg CO_2-equivalent per produced kWh of battery cell, depending for variation on the type of lithium-ion chemistry, as well as the producer. As the production of cells does not differ for maritime systems, the emission of $CO_2$from production of the E-ferry batteries can roughly be calculated at between 215-430 tons, an amount, that, when compared to the fossil fuel consumption of the comparable diesel-electric LMG-50.1, would equal the emissions of 3 months operation with this vessel, this being the case even if the E-ferry prototype was operating on electricity from the Danish mix grid, rather than on certified green electricity.

5.4.1 Operational evaluation of environmental impact

Local emissions from a fully electric vessel such as the E-ferry prototype are by nature non-existent, since no type of fuel is burned on the ship (or shore) directly, either to supply the engine with energy directly, or via a diesel-electric generator. E-ferry operator Aeroe-ferries have, moreover, chosen to use certified green electricity for charging the E-ferry, though this is at an additional cost, compared to using the standard Danish grid mix, which include about 40-50% electricity generated from fossil fuels (oil, coal and natural gas). Currently, due to national rules, it is not in general possible for a private (or public) operator to produce the energy used themselves, nor to source electricity directly from e.g. the existing wind mills on Aeroe, which currently produce more than 120% of the island's electricity consumption. The green certificates bought per kWh by the operator are thus the best current way of ensuring that the E-ferry prototype is entirely emission free, also in a more global perspective, as the green certificates correspond to extra payments to renewable energy producers who put up new supply of wind, solar or hydro power to the grid. The trading of green certificates is for now taken care of by the electricity trading and supplying companies, but it could also be arranged by the ferry operator in a bilateral agreement with local renewable energy providers at a later stage. With the purchase of electricity using such methods it could be argued that the operation is also emission free resembling a broader well-to-propel aspect. However, this discussion remains controversial in public opinions.

For the overall evaluation, three different emission saving numbers has consequently been prepared, and is presented in *Table 52* below: First, the emissions savings of the E-ferry prototype when operated with green electricity only, as compared to when operated with electricity from the standard Danish grid mix of 2019. Secondly, the green electricity savings of the E-ferry as operated currently is compared to the two alternative vessels where the energy consumption of these two vessels where calculated for the E-ferry prototype operation profile in Section 5.3.5.1 and 5.3.5.2. Savings are provided per year. The emission factors used for these calculations are from Energinet Miljødeklaration 2019, Kristensen 2012, and Wismann/Miljøstyrelsen 2000.

Table 52: Emission savings from one year of operation with E-ferry prototype compared to other modes of operation.

Emission savings per year	**CO_2**	**NO_x**	**SO_2**	**CO**	**PM_{10}**
E-ferry green electricity versus Danish grid mix 2019	510 tons	680 kg	102 kg	442 kg	34 kg
E-ferry versus newbuilt diesel-electric tier III ferry (LMG50.1)	2.520 tons	14.330 kg	1.550 kg	1.791 kg	542 kg
E-ferry versus existing diesel tier I ferry (MF/Marstal)	3.888 tons	70.797 kg	2.403 kg	3.218 kg	1.442 kg

Other comparisons can be calculated directly from *Table 52* by subtraction and finding differences. E.g. a newbuild diesel-electric ferry (LMG50.1) replacing an old existing diesel ferry (M/F Marstal) on the route would save 3888-2520 = 1368 tons of CO2 annually. Moreover, it can also be calculated from Table 59 that should the E-ferry operator choose not to buy green certificates, the reduction of Co2 emissions for the E-ferry compared to the alternative vessels would still be of a factor 5-7. For other types of emission savings, e.g Oxides of Nitrogen (NOx), Sulphur Dioxide (SO2), Carbon monoxide (CO) and Particulate Matter (PM) savings are of even higher factors and order of magnitudes. Overall, it can be said that the emissions from the Danish grid mix has decreased quite dramatically over the last 10 years, due to a higher mix of renewable energy sources, from wind and solar installations both in Denmark and neighboring countries to which the Danish grid has access. This is illustrated in Figure 54 below.

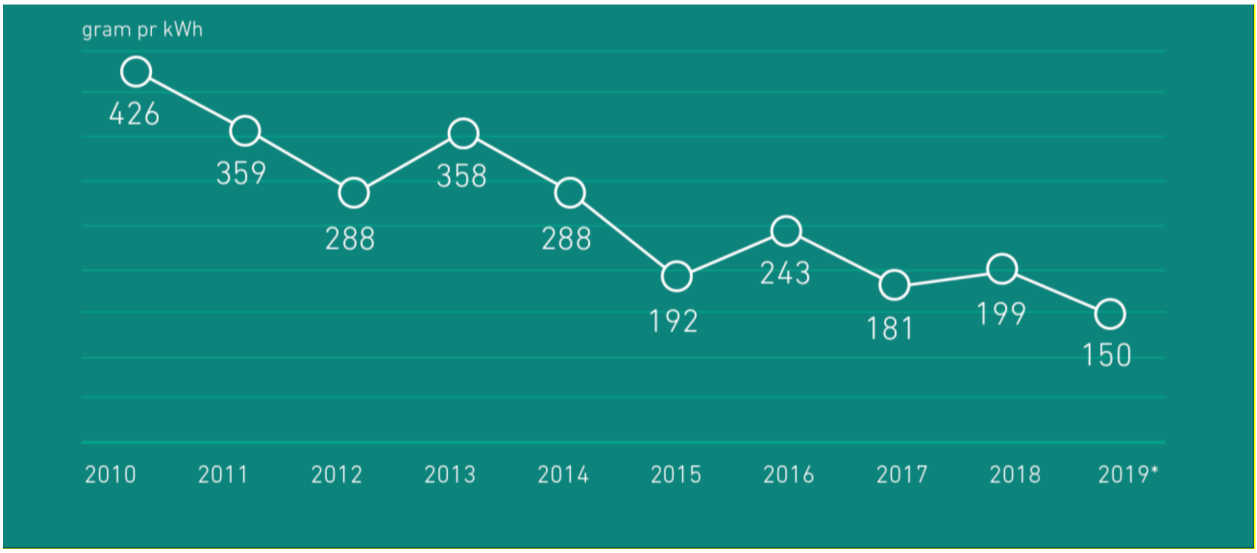


Figure 54: CO2 equivalent climate impact of Danish grid electricity mix per kWh. Energinet.dk *Number not finally evaluated.

The same trend applies across Europe, though here data up to 2016 only is available, as illustrated in Figure 55:

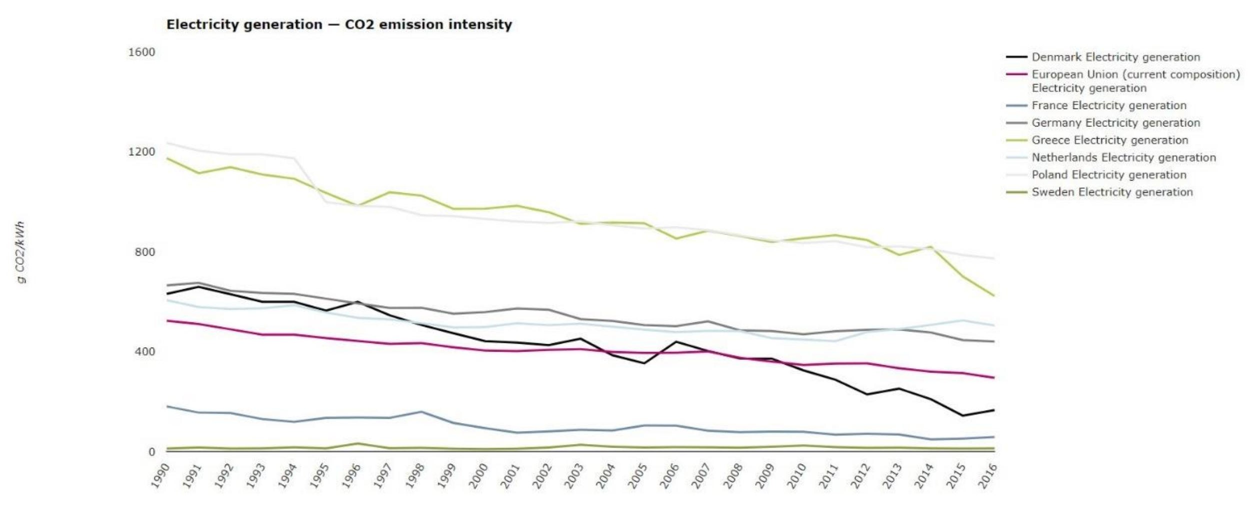


Figure 55: Trend in CO_2 emission intensity from electricity generation in selected EU countries, Data EEA Eionet, latest update.

In *Table 53* below, the CO_2 intensity from electricity generation for various European countries has been used to calculate the CO_2 savings if the E-ferry prototype was operated in any of these countries and supplied with the grid mix electricity (i.e. without green certificates). This Table reveals that in some countries (Sweden, France and Finland), the savings on CO_2 emission would be even higher than for the E-ferry current route in Denmark (when supplied with grid mix electricity).

Table 53: ***Newest EU data from EEA and Eionet (2016) and based on calculation of energy consumption from comparative study including port stay and hotel power.***

EEA Eionet data 2016		CO2 savings E-ferry grid mix	
EU country	**CO2 intensity national grid mix**	**New diesel-electric ferry**	**Existing diesel ferry**
Sweden	13,3 g/kWh	2.442 tonnes	3.810 tonnes
France	58,5 g/kWh	2.299 tonnes	3.667 tonnes
Finland	112,8 g/kWh	2.128 tonnes	3.496 tonnes
Denmark	166,1 g/kWh	1.959 tonnes	3.327 tonnes
Italy	256,2 g/kWh	1.675 tonnes	3.043 tonnes
Spain	265,4 g/kWh	1.646 tonnes	3.014 tonnes
United Kingdom	281,1 g/kWh	1.596 tonnes	2.964 tonnes
EU Average	295,8 g/kWh	1.550 tonnes	2.918 tonnes
Germany	440,8 g/kWh	1.092 tonnes	2.460 tonnes
Netherlands	505,2 g/kWh	888 tonnes	2.256 tonnes
Greece	623,0 g/kWh	516 tonnes	1.884 tonnes
Poland	773,3 g/kWh	41 tonnes	1.410 tonnes
Estonia	818,9 g/kWh	-103 tonnes	1.266 tonnes

5.4.2 KPI – environmental evaluation

The main indicators on which the E-ferry environmental evaluation has been based, and which the above analysis and discussion have evaluated, are as follows:

Table 54**: Indicators to be assessed for the environmental evaluation (E-ferry emissions based on green certified electricity)**

	Indicator	Unit	Compared to EFD[26] (M/F Marstal)	Compared to BAT[27] (LMG50.1)	Comment
1	Reduction in GHG emissions	N/A			

[26] *Existing Ferry Design, i.e. M/F Marstal on E-ferry route*
[27] *Best Available Technology, i.e. LMG-50.1 on E-ferry route*

2	Reduction in air pollution	N/A	In reality unmeasurable, but E-ferry emits neither GHG nor pollutes the air, so the reduction could be considered 100%		
3	Reduction in NOx emissions	kg/year	100%	100%	Reduction of respectively 71.000 and 14.000 kg
4	Reduction in SO_2 emissions	kg/year	100%	100%	Reduction of respectively 1.550 and 2.400 kg
5	Reduction in particulate matter (PM)	kg/year	100%	100%	Reduction of respectively 540 and 1440 kg
6	Reduction in CO_2 emissions	tons/year	100%	100%	Reduction of respectively 3.900 and 2.500 tons
7	Reduction in energy used	kWh/year	See section 4.2		
8	Noise Limit	Db	Noise limits are defined by Maritime Authorities onboard vessels as below 70 Db. Perception of noise is reported in Section 4.4		
9	Perception of noise	N/A			
10	Reduction in wake waves	N/A	Not measured/measurable		
11	Risk of oil pollution	N/A	Risk of oil pollution is eliminated		
12	Energy efficiency ratio	Up to 94%	See section 4.1		

5.5 Societal evaluation

The societal evaluation of the E-ferry prototype focuses on the potential impacts that the construction and implementation of the E-ferry has had on (a) its users/passengers and (b) its developers and operator. These impacts are determined through 2 questionnaires, one for users and one for the business- and industrial partners involved in the E-ferry project, including also the subcontracting companies.

5.5.1 User/passenger evaluation

The passenger evaluation of the E-ferry in operation has as its general aim to assess the degree to which the implementation of the E-ferry had impacts on the passengers, as well as their use of ferry transportation more generally. To gather information on this, a questionnaire was developed, where passengers were asked to evaluate their general satisfaction with the E-ferry, its various features, and on their own pattern of travel and how/whether the electrification of marine transportation would potentially change this pattern of travel. In addition to the English version, the questionnaire was also translated into Danish. The questionnaires were made available on-board the E-ferry from period 6 of the evaluation (November 2019), i.e. after the docking for optimization in period 5, and throughout the remaining evaluation period (end May, 2020). The passenger evaluation period didn't start before period 6 in order to avoid contamination of answers from various technical issues that caused delays and cancellations during the trial period up until period 5. It was further decided, that to avoid any bias or feelings of pressure on the passengers (and crew), that the questionnaires would be available for voluntary use, rather than having the crew hand out questionnaires in a more systematic fashion. This is illustrated in Figure 56, below. While the result of those decision clearly has been that fewer questionnaires have been filled out, it also means that the quality of the submitted questionnaires is higher than had every passenger been obliged to fill one out.

***Figure 56*: Questionnaires made available on-board the E-ferry**

A further complication for the number of questionnaires eventually collected for the overall passenger evaluation occurred with the COVID-19 pandemic, which from early March 2020 led to severe restrictions on travel in Denmark. As for all other public transport in Denmark, the passenger numbers decreased significantly during this period. This is illustrated in *Figure 57*, which shows the steady decrease in passengers and cars transported during March 2020, at a time of year where E-ferry operator Aeroe-ferries otherwise in general begin the spring- and tourist season with increasing passenger numbers to follow.

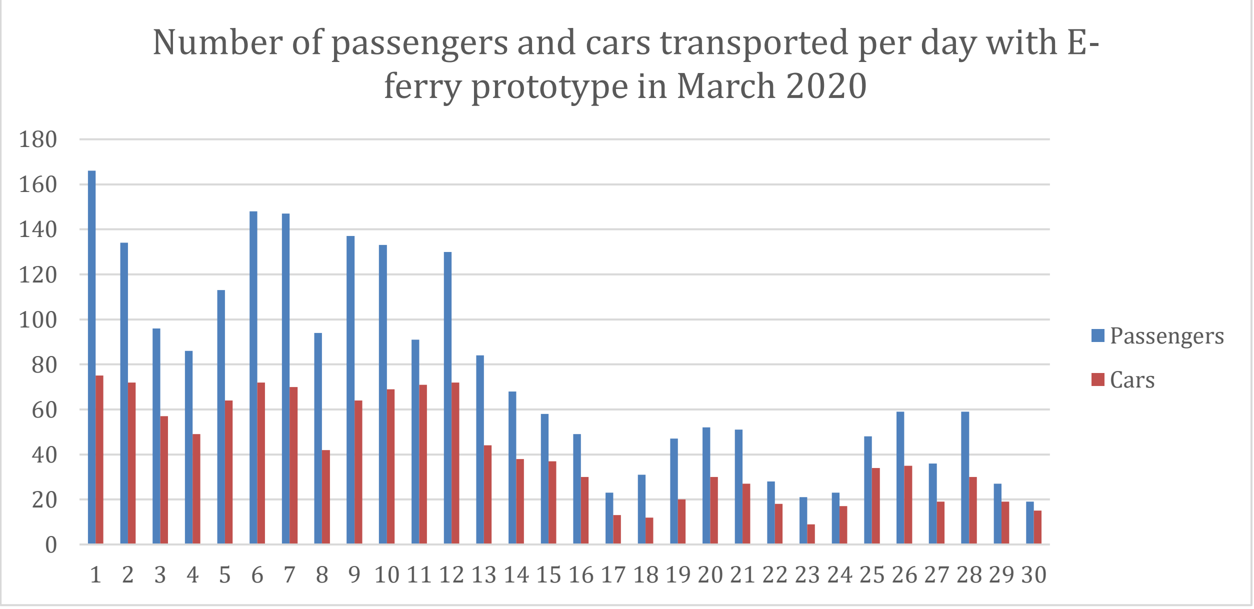
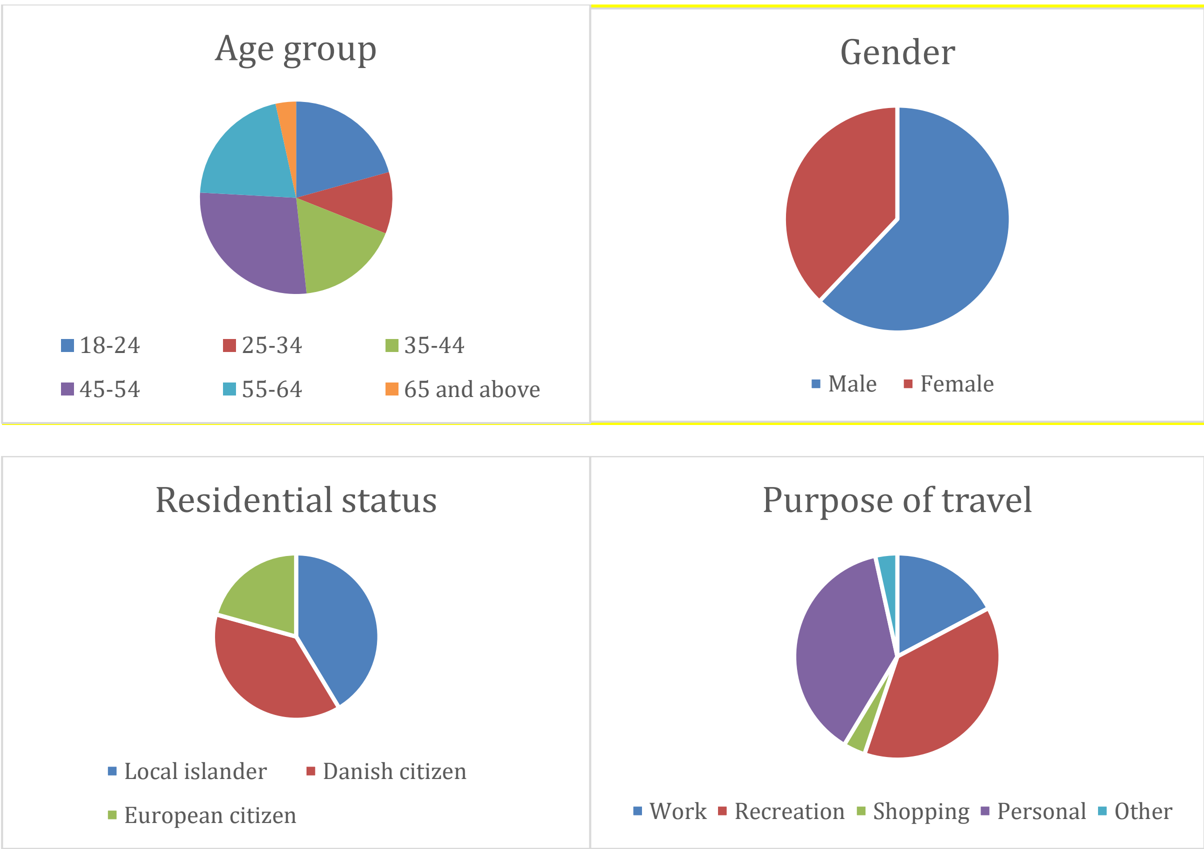


Figure 57: Effect of Covid'19 on passengers and cars transported on the E-ferry prototype during March 2020

As passengers travelling in car was prohibited from entering the passenger salon during the COVID-19 pandemic, and the questionnaires were available only there, no questionnaires were in fact collected for the whole period of March-May 2020. As a consequence of these various contingencies, a total of only 29 questionnaires have been submitted and analysed for the current evaluation. The small number of questionnaires analysed means that the results are not statistically significant, but it is nevertheless possible to extract some general trends from the answers provided, as will be done in the following sections.

5.5.1.1 Passenger profile

The general passenger profile(s) gathered from the questionnaires can be gaged from Figure 58, where information about age group, gender, residency and frequency and purpose of travel is provided:



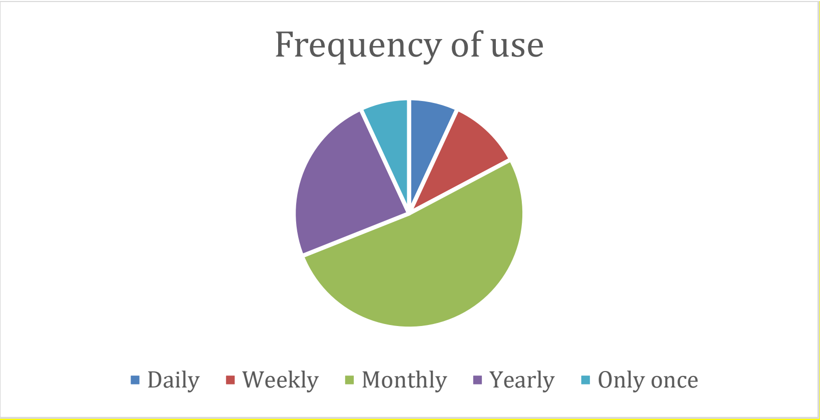


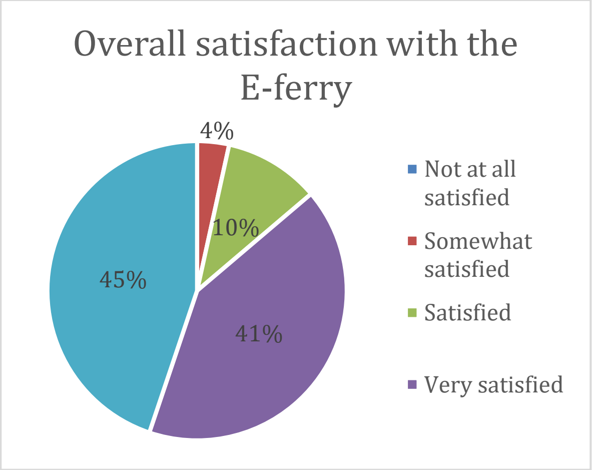
***Figure 58:* Passenger profile for E-ferry prototype**

As can be seen from the figure above, the typical E-ferry user (or at least the typical questionnaire submitter) is likely to be a male in the age between 45-64, with local residency on the island. The typical traveller uses the E-ferry a couple of times a month, for the purpose of visiting family or friends, going on holiday or other recreational purposes. It is likely that the passenger profile changes significantly as the tourist-season begins, but due to the COVID-19 pandemic, this has not been possible to confirm.

5.5.1.1 Passenger satisfaction

For the evaluation of the E-ferry, passengers were requested to answer to some questions about their general satisfaction with the E-ferry. With a single exception[28], all passengers rated their level of satisfaction with the E-ferry overall as either 'very satisfied' (41.3%), or 'extremely satisfied' (45%). All passengers answering the questionnaire were already aware that the vessel they were on board was fully electric and had first heard about the E-ferry before, either from newspapers, from friends or relatives, or from other sources. Given the passenger profile outlined above, this makes a lot of sense, since the E-ferry project was covered widely during the construction phase in local and regional newspapers and of much discussion on the island. The overall distribution of passenger knowledge and evaluation is illustrated in Figure 59 below.

[28] The exception was by a local resident, who it seems was generally dissatisfied not with the E-ferry as such, but with the fact that the E-ferry was operating from a different town than the passenger's town of residence.



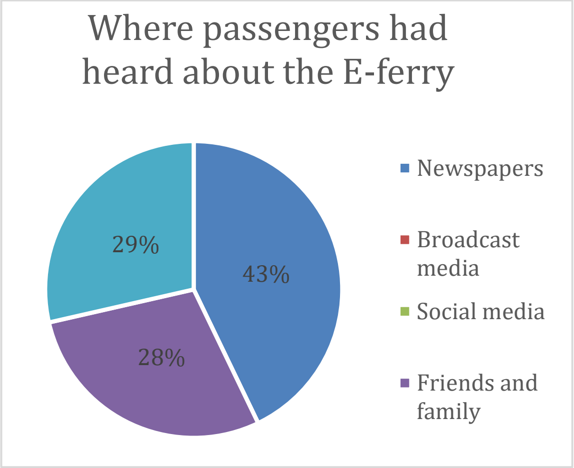


***Figure 59:* Overall satisfaction with and knowledge about E-ferry**

Due to the questionnaire's details, we are also able to provide a more nuanced picture of passengers' overall satisfaction with the E-ferry, as they were asked to rate this in relation to 7 specific areas: safety, comfort, travel time, noise level, environmental friendliness, frequency and reliability. Ratings for these features are illustrated inFigure 59. Moreover, passengers were requested to rate the same features in relation to other ferries, these ratings are illustrated in Figure 60.

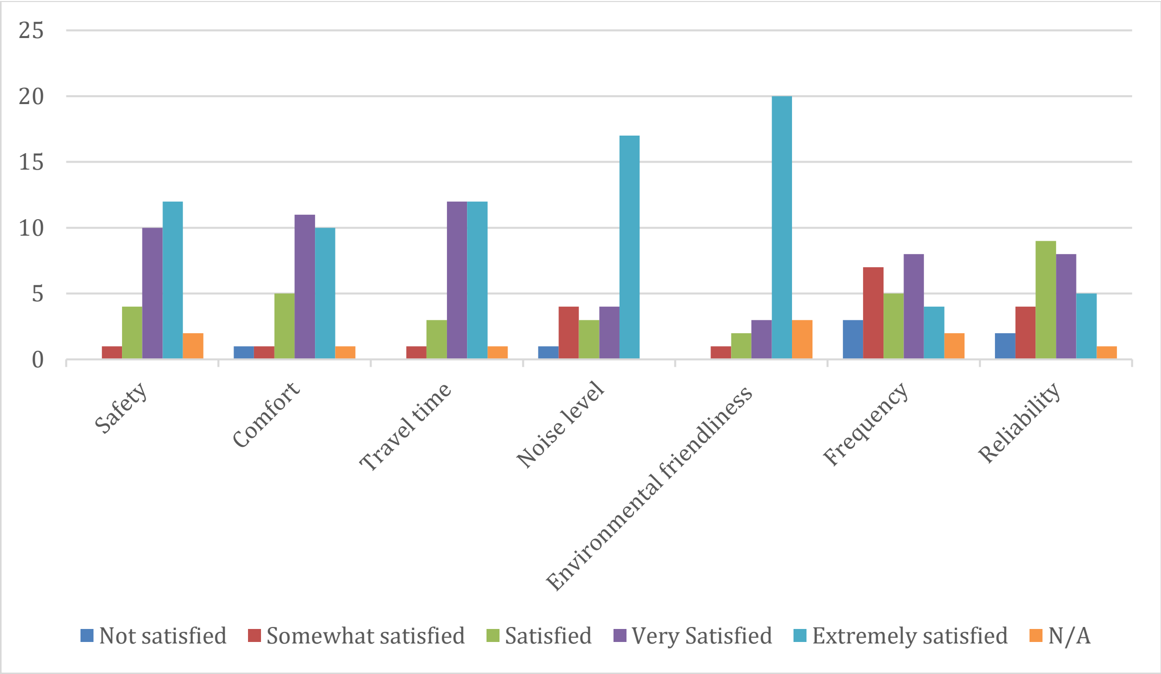


***Figure 60*: Evaluation of E-ferry on specific areas**

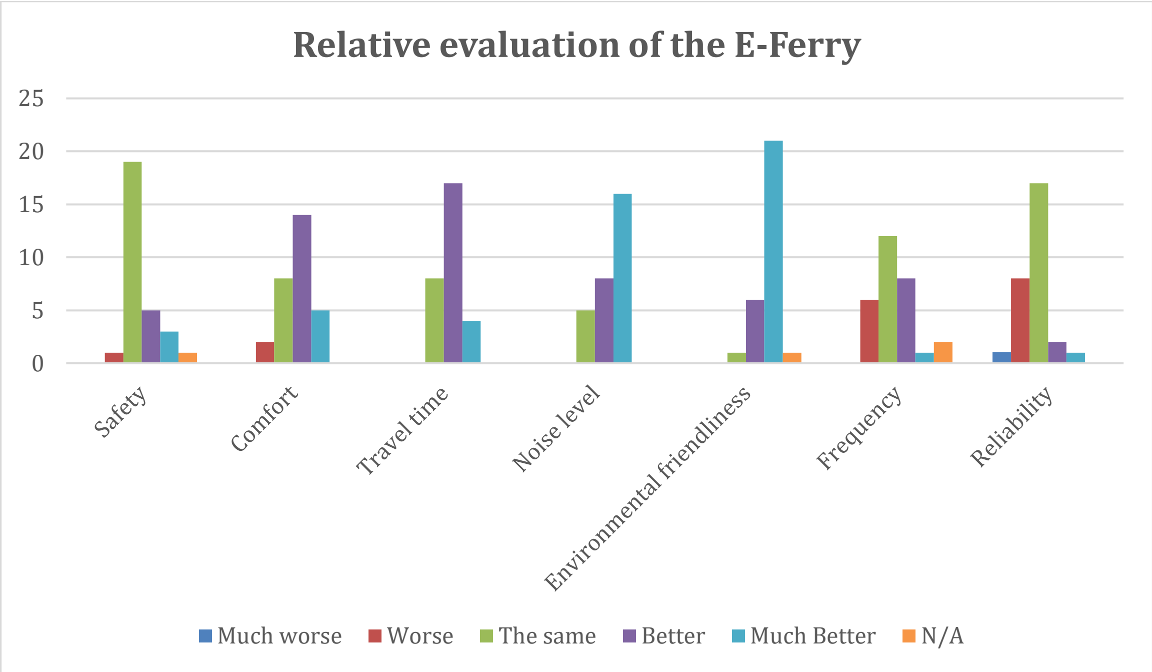


***Figure 61*: Relative evaluation of E-ferry and other ferries**

As is evident from the distribution of responses, the E-ferry is evaluated positively, by and large, on areas such as Safety, Comfort, Travel time, Noise level and – not surprisingly – Environmental friendliness; in all these categories, the majority of respondents are either 'Very satisfied' or 'Extremely satisfied'. For four of these categories, we can also see that passengers rate these higher when comparing to their experience with other ferries, i.e. that they evaluate that the E-ferry is more environmentally friendly, has a shorter travel time, better comfort and less noise. See Figure 61. The category Safety is here an exception, though passengers rate the safety onboard the E-ferry highly, they typically do not consider the safety level of the E-ferry as being higher than on other ferries. As safety is by most passengers, and particularly perhaps for those passengers that are local residents and hence frequent users of ferries in general, probably considered an area that is regulated and determined by the Maritime Authorities, it seems reasonable to assume that passengers for this aspect of the E-ferry are simply confirming that their expectations about general safety on board the E-ferry has been met and that they are – naturally – satisfied or even extremely satisfied with that.

For better understanding of how passengers think and evaluate the services of E-ferry we take a closer look on data. Specifically, a Spearman correlation test performed among questions for two separate sets. Spearman coefficient is a non-parametric (variables don’t follow Normal Distribution) measure that shows the correlation between two variables which take rank values. The first set contains all the parameters that were illustrated in Figure 61, along with overall satisfaction, as illustrated in Figure 62, below:

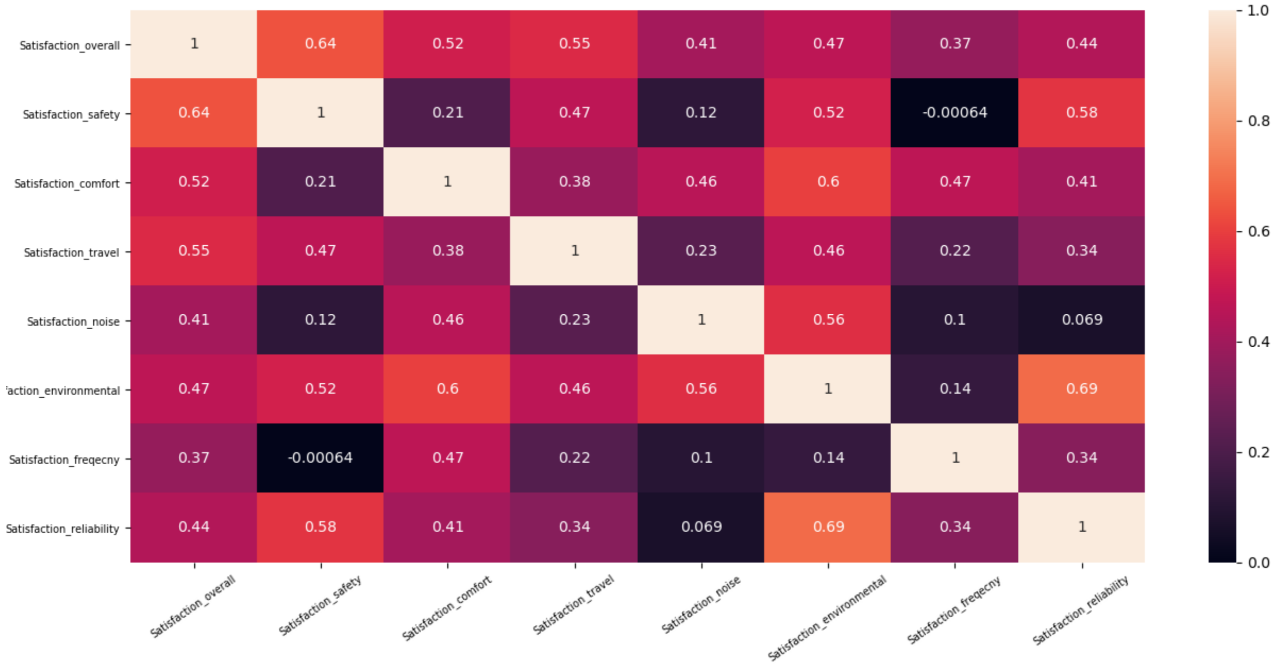


***Figure 62*: Spearman Correlation Coefficient among Satisfaction Features.**

At first sight, there is no really powerful correlation (>0.8) among these variables (Table 25). However, some factors seem to have significant relevance to each other. The overall satisfaction is correlated with safety by $\rho = 0.64$, and with travel time with $\rho = 0.55$. Moreover, in order to verify these results, we performed the Kruskal-Wallis test which is an alternative of ANOVA and can be used for rank variables. As a result, satisfaction with level of safety can be seen to affect the overall satisfaction with statistical significance (p-value = 0.0009), and the different levels of satisfaction of travel time also contributes (p-value = 0.02) to overall satisfaction. The rest of the variables do not seem to have any statistically significant correlation with overall satisfaction. These results mean that the overall passenger experience with E-Ferry depends on the safety and travel time experience they have. Thus, the safety and travel time service level can be characterized as good or satisfying, considering the answers in Figure 60, which shows that 86% of passengers respond to be ‘satisfied’ or ‘very satisfied’ with their experience of the service. Similar outcomes can be produced by looking at the rest of the variables in Figure 61. Safety, for instance, is partially correlated with reliability (ρ = 0.58), and reliability is significantly correlated (ρ= 0.69) with the environmental properties of the boat. These results can be used as a guide for future improvements on E-ferry services.

When the same methods are applied to the information provided in Figure 62bove, where passengers compare the E-ferry prototype with other known ferries, we do not find any correlations with the Spearman Correlation Coefficient, except between relative noise and relative environmental impact, as illustrated in Figure 63.

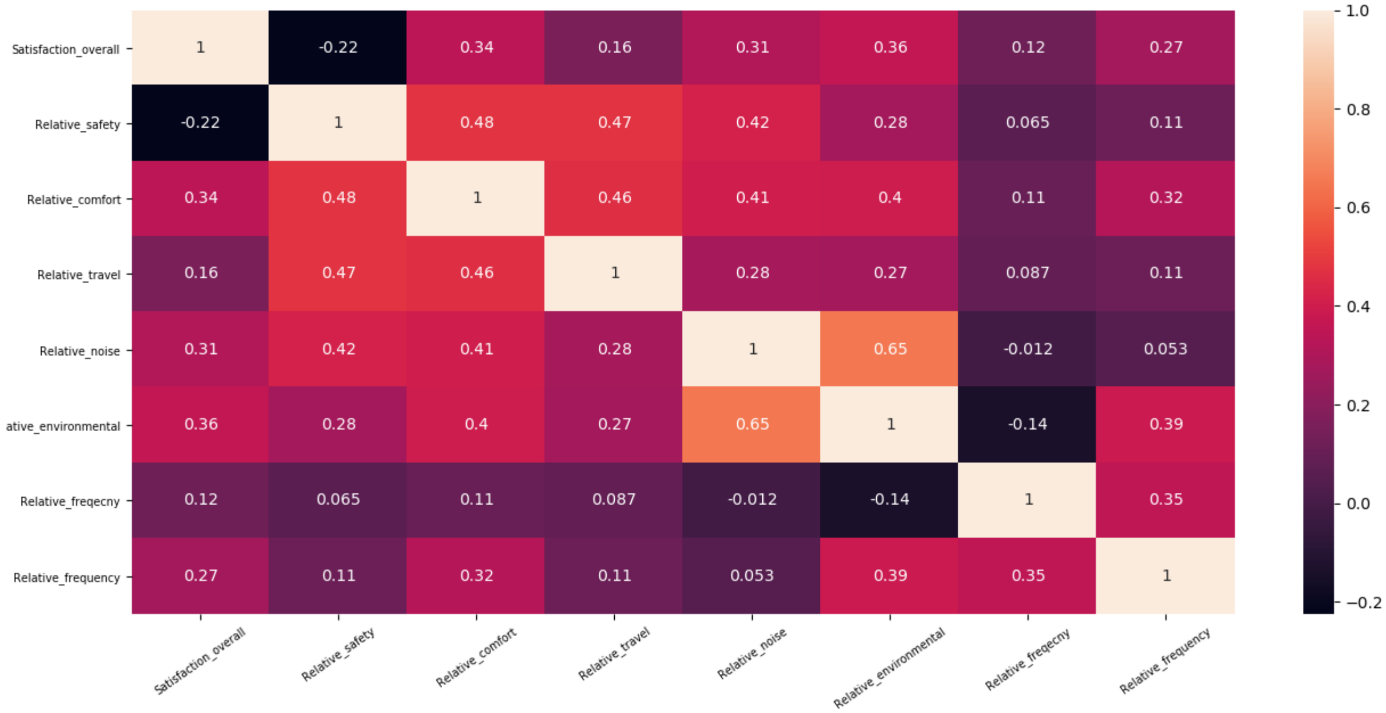


***Figure 63*: Spearman Correlation Coefficient among Relative Satisfaction Features.**

The overall lack of correlation in Figure 63 is confirmed through the Kruskal-Wallis test, which gives statistical independence with statistical significance of 0.05. Although it could be expected that the factors evaluated would have an impact on overall satisfaction, that does not appear to be the case, at least from a comparative point of view, where the E-ferry is compared to another vessel. However, it may be that case that the somewhat small sample (29 instances) of questionnaires makes it impossible to conclude anything with statistical significance from the above Figure 63.

5.5.1.2 Passenger predictions

The final part of the passenger questionnaire poses questions about how passengers evaluate or predict the degree to which the implementation of the E-ferry prototype in operation will influence their travel and transportation patterns. Figure 64 presents the passengers’ answer to whether the E-ferry operation is likely to increase the frequency of their transportation, to which more than 50% answer positively. More precisely, 20.7% of passengers respond with ‘definitely’ and 31% with ‘probably’.

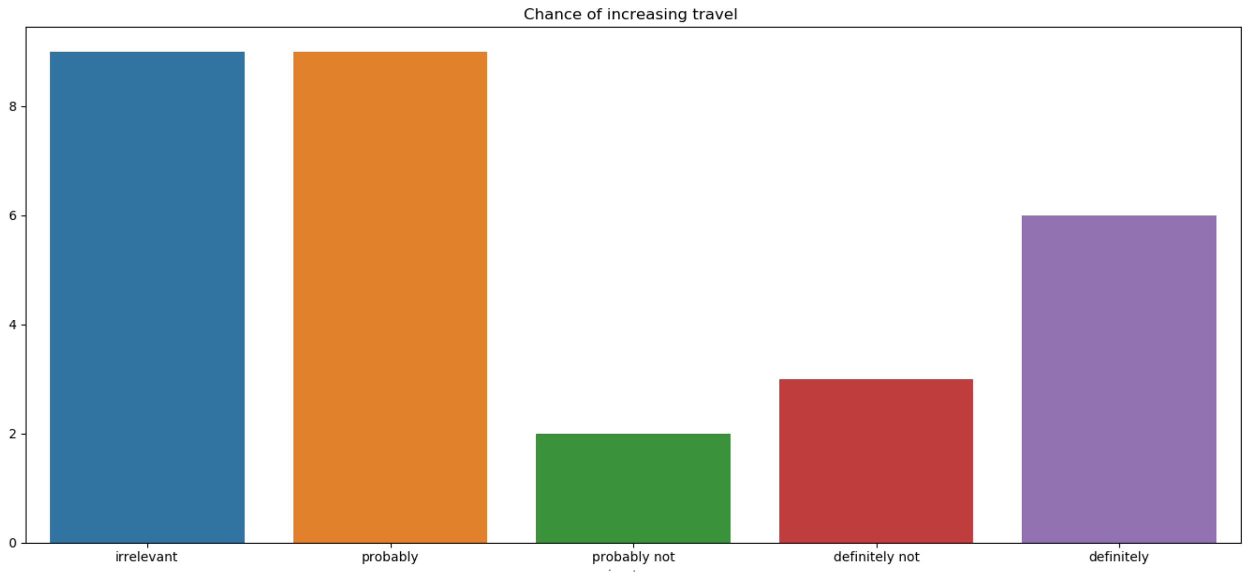


***Figure 64*: Would you increase the frequency of your trips due to the operation of E-ferry?**

Given that passengers are overall satisfied, very satisfied or even extremely satisfied with the E-ferry prototype, it may seem disappointing that only half of all passengers believe that the E-ferry prototype may result in them increasing the frequency of their travel. However, if we consider Figure 65 below, we can see that what would typically motivate passengers to increase their travel frequency is the frequency of the ferry operation, i.e. the number and scheduling of trips per day.

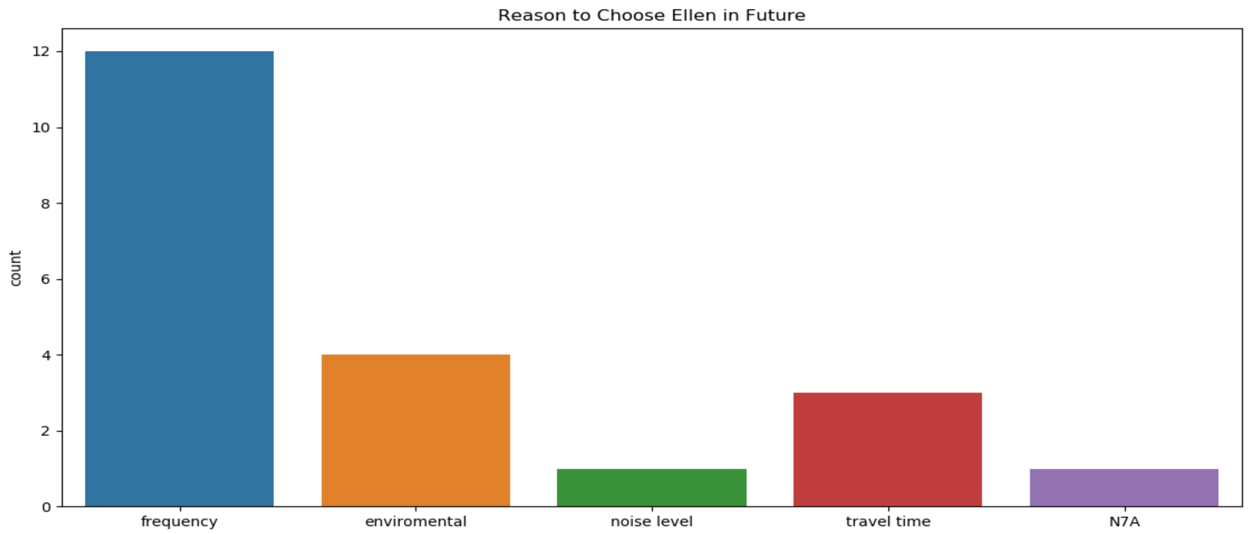


***Figure 65*: Which reasons would you have for increasing your frequency of using the E-ferry prototype**

Though also the reduced travel time and the environmental friendliness figure as reasons for increased travel, 57% of the passengers listed the frequency of the operation as their main motivation for using the ferry service more often than at present. Considering the overall passenger profile illustrated in Figure 58, from which we know that the typical E-ferry passenger for the period evaluated is a local resident, using the E-ferry a couple of times a month, for the purpose of visiting family or friends, going on holiday or other recreational purposes (e.g. shopping on the mainland), it is perhaps not surprising that the aspect of frequency is the most relevant for them. However, as I illustrated in Figure 66 below, this does not mean that passengers overall do not support the electric ferry solution. Thus, the last conclusion from the passenger questionnaire, illustrated in Figure 66, below, is that electric vessels are important for environmental reasons.

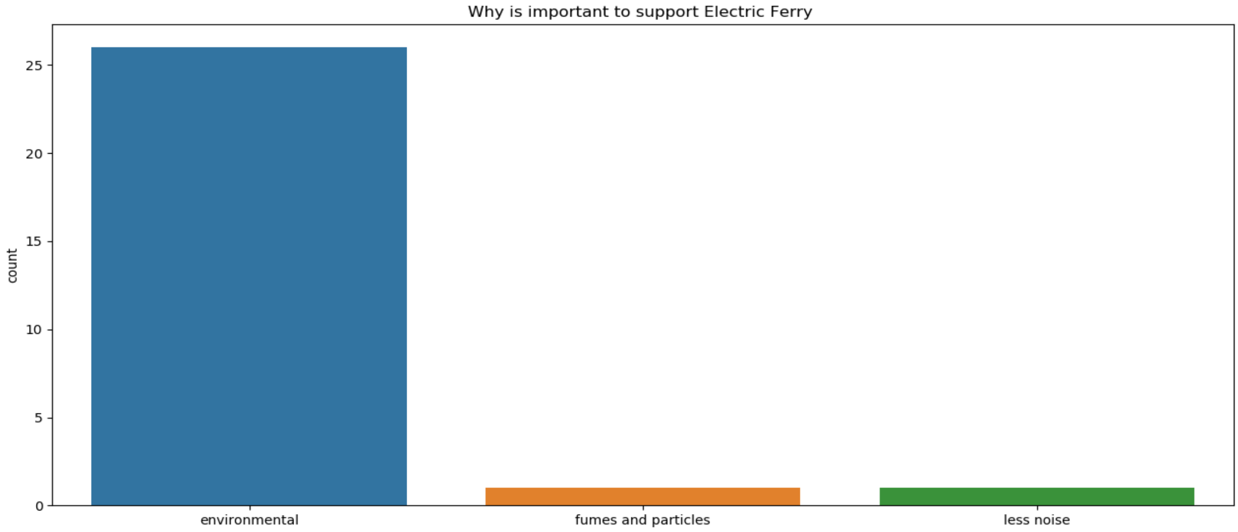


***Figure 66*: When new ferries are built, do you think it's important that they be electric? What is the most important reason?**

5.5.2 Industry evaluation

The scope of the industrial evaluation is to assess the overall impact that participating in the E-ferry project and via this contributing to the development and generation of new technology, skills and knowledge for the electrification of future marine vessels has or will have for the industrial partners taking part in the building and construction of the E-ferry. To measure the necessary indicators, a questionnaire was designed and sent out by mail during the last half of the overall evaluation period, to each of the E-ferry industrial partners, who were all given 3 months to complete the questionnaire and – where relevant – request subcontractors who had contributed significantly to the E-ferry project, to also responded to the questionnaire. All industrial E-ferry partners and 3 subcontractors complied with the request, given a total of 7 respondents to the questionnaire and the below results. The questionnaire was comprised of 2 sections and a total of 12 standardized questions, some of which contains multiple-parts, allowing for multiple-responses. Indicators to be assessed aimed to cover two main areas, in the overall area of employment/jobs:

- New jobs' creation in the sector of maritime production and other supporting businesses;
- Eliminated jobs related to lower manning requirements.

As discussed previously, the construction and approval of the E-ferry prototype has indeed resulted in a lower safety manning requirement than what is otherwise the case for operator Aeroe-ferries other conventional ferries that are diesel-driven and do not have automooring. The reduction of jobs based on the safety manning approval is 2 persons, equalling up to 6 positions for a year of operation, as the E-ferry prototype is approved – and technically able to operate with two navigators and one safety crew, with neither engineer or able seaman required. For practical purposes of maintenance and service, however, E-ferry operator has chosen to have a full-time engineer dedicated to the E-ferry prototype, as well as some hours of assistance weekly from an able seaman for general maintenance. As calculated before, a total of 10,86 crew per month is currently dedicated to operating with the E-ferry prototype in this constellation, whereas the alternative LMG-50.1, which can be considered the best available technology otherwise, would require a crew of 11,94 per month, giving a reduction or loss of job due to the E-ferry prototype of 1 position. If compared to operating with an existing, older vessel, such as M/F Marstal, the reduction or loss would be close to 4 positions, as operation of this vessel would require a total crew of 14,64 per month. These numbers have been used for the final KPI evaluation below, for which reason it was also decided not to include E-ferry prototype operator as a respondent to the questionnaire, which could instead be more focused on the production part of the project.

6.2.2.1. Survey results

The 7 respondents to the questionnaire were first asked to define with which of the E-ferry's life stage they were involved, choosing between one or more of the four life stages already defined in the questionnaire: 1) Construction, 2) Fuelling/charging, 3) Operation, and 4) Installation and maintenance of equipment. The majority (71%) of companies reported to be involved in a single life stage, whereas the remaining 29% were involved in two or more life stages. More specifically, 57% were involved with construction, 43% with fuelling/charging, 29% with operation, and 86% with installation and maintenance of equipment.

Independently of where they defined themselves to be on the E-ferry life stage scale, all of the respondents answered positively (100%) with respect to whether new jobs are expected to arise in their respective organizations, due to the introduction of electric propulsion systems in maritime transportation and their involvement in the E-ferry project. Though it has been suggested in general that the introduction of new technologies can lead to loss of jobs and reduced wages (Sachs and Kotlikoff 2012), none of the respondents expected this to be the case within their organizations, though of course, as noted above, this does apply to the main operator of the new technology, i.e. the Aeroe-ferries, who was not a respondent. Based on the expectation of the creation of new jobs, respondents were then asked to provide a sample of specific job roles and opportunities that may be created due to the introduction of electric propulsion systems in maritime transportation. These job roles and (number of new positions where available) are:

- Increased number of positions in the new building departments (3)
- New positions in the installation of Battery/DC system on electric ships (hybrid)
- New positions in installations of power system and battery management (2)
- New positions as project manager, lead engineer, project engineer and technical sales engineer for marine business line (4)
- New positions in automation engineering

Focusing on the new job roles and positions expected to be created from the E-ferry project, the companies were further asked how they expected these jobs to affect the need for specialization, as opposed e.g. to training of existing employees; and whether it would be necessary or relevant for the companies to update job regulations and policies or to acquire additional land to expand company activities. Figure 67 presents the responses provided on a Likert scale using a five-point scale of agreement (i.e., None, Marginal, Moderate, Considerable and High).

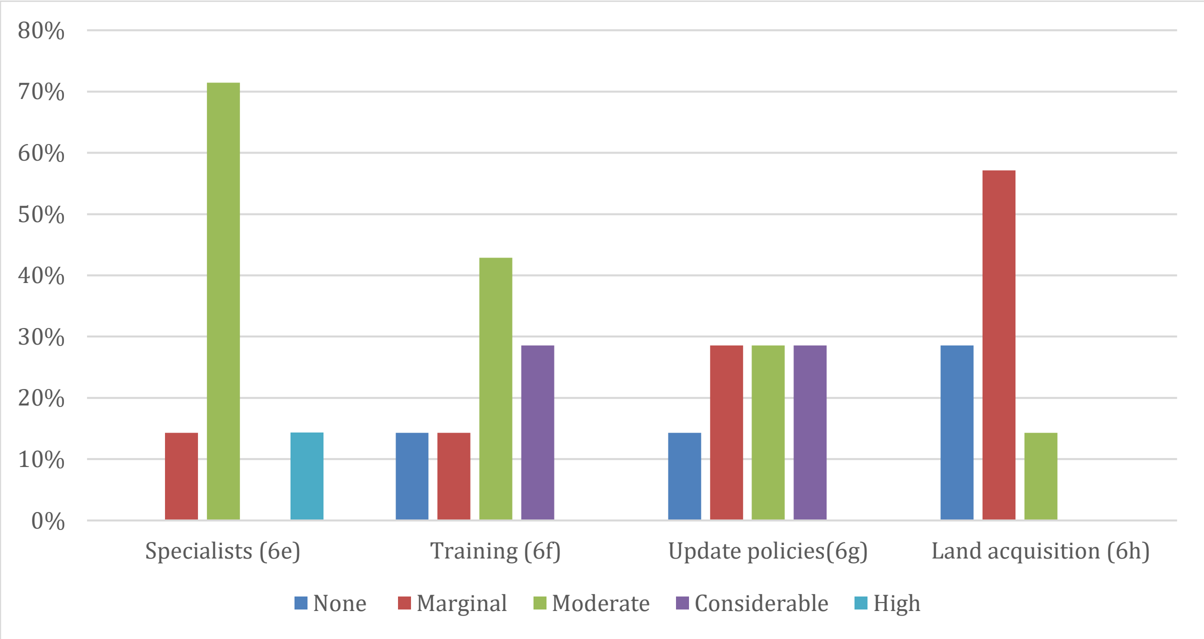


Figure 67. Increased number of professional specialists (6e); Training of existing employees (6f); Updating job regulations and policies (6g); Acquisition of additional land to expand company activities (6h)

As illustrated in Figure 67 above, companies expect that the new jobs to be created are likely to require an increased number of specialists, with a total of 85% of the respondents answering that this is highly or moderately related (6e); a finding that is supported by literature as there is a positive correlation between automation and experts (Bughin et al. 2018). Of note in this respect is also that many respondents answered that new jobs could also be associated with training of existing employees (43% moderately and 29% considerably), which may to some degree account for the fact that no loss of job would be expected, as the different organizations would instead consider training their existing employees to new professional standards of specialization.

Respondents appear to mainly agree on what degree of relevance the creation of new jobs will have on their need to update job regulations and policies (6g), as 14% answered that they expected no changes, 14% expected marginal changes, 43% moderate changes and 29% considerable updating of their job regulations and policies. Linking these responses to the overall life-stage of the E-ferry, it was found that respondents who placed themselves in the life-stage of construction, fuelling and operation are more likely to expect moderate of considerable updates of job regulations and policies, than those companies in the life-stage of installation and maintenance of equipment. Finally, the company's overall did not report any (or only moderate) expectations for acquiring new land as a direct consequence of the creation of new jobs, as 29% did not expect to acquire any new land and 57% expected only a marginal effect of this.

As illustrated in Figure 68, below, companies were also asked to access the degree to which new jobs would be related to other organisational changes, i.e. merger or acquisition of/with another company to expand/support activities, relocation of headquarters, offices or factories, or relocation of staff.

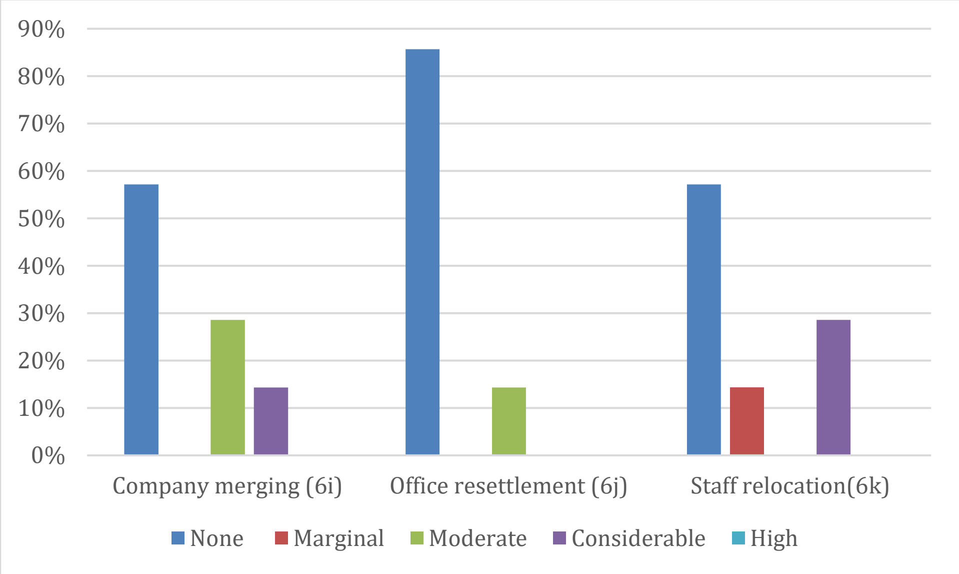


Figure 68. Merge or acquisition of other company to expand/support activities (6i); Resettlement of headquarters or offices due to new job activities (6j); Relocation of existing staff (6k)

As illustrated in Figure 68 above, more than half the companies did not expect that the new job roles would be related to mergers or acquisitions, though the other, smaller half answered that new jobs roles are moderately or considerably related, respectively, to merge or acquisition of other company to expand/support activities (6i). The majority of respondents answered that neither relocation of headquarters, offices or factories (86%) nor relocation of existing staff (57%) is relevant due to the new job activities, though for the latter aspect about a third (29%) did believe that relocation of existing staff is potentially relevant due to new job roles and activities.

Finally, the companies were asked to evaluate to what degree the new job roles created are related to increased health risks, increased safety risks, improved job quality or increased salary, summarized in Figure 69, below:

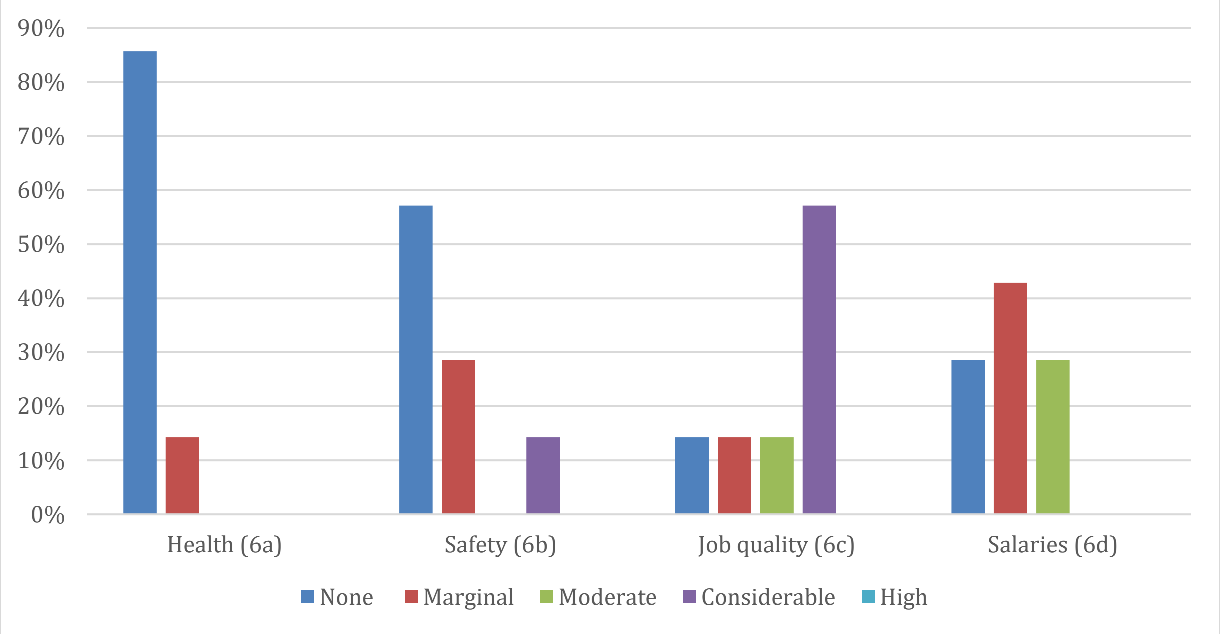


Figure 69: Increased health risks (6a); Increased safety risks(6b); Improved job quality (6c); Higher overall salaries/wages (6d)

Respondents answered that the new job roles are not related (86%) or marginally related (14%) to increased health risks (6a) and likewise, the majority answered that the new job roles are either not related (57%) or marginally related (29%) to increased safety risks (6b). 14%, did however, reply that the new jobs are related to increased safety risks. Whereas the negative effects of the new job roles created are thus by and large negligible, the positive effects were rated higher. Thus, 57% of the respondents estimated a considerable improvement in job quality (6c), though overall increase in salary was only rated as moderately related to the new jobs by 29% of the respondents. Table *55* provides a summary of the overall results of Figures 72-74.

Table 55: Summary of results - At what level the new job roles are expected to be related to

	None	Marginal	Moderate	Considerable	High
Increased health risks	86%	14%	0%	0%	0%
Increased safety risks	57%	29%	0%	14%	0%
Improved job quality	14%	14%	14%	57%	0%
Higher overall salaries/wages	29%	43%	29%	0%	0%
Increased number of professional specialists	0%	14%	71%	0%	14%
Training of existing employees	14%	14%	43%	29%	0%
Updating job regulations and policies	14%	29%	29%	29%	0%

Acquisition of additional land to expand company activities	29%	57%	14%	0%	0%
Merge or acquisition of other company to expand/support activities	57%	0%	29%	14%	0%
Resettlement of headquarters or offices due to new job activities	86%	0%	14%	0%	0%
Relocation of existing staff	57%	14%	0%	29%	0%

Finally, the respondents were asked to evaluate how the specialization (new job roles) would benefit their competitiveness as companies and increase their annual production, to which as 86% of respondents responded positively. The shift to electric propulsion systems is thus overall evaluated as being accompanied by new technologies and new job roles, which are expected to enable mass customization[29] according to roughly half (57%) of the respondents' answers. The questionnaire provided the opportunity to company partners to share their thoughts regarding potential issues that have been faced and provide their overall experience while working on the E-ferry project. Based on the feedback, the project partnership for such an innovative and research project is a demanding and difficult process to control. A huge amount of learning is included in the overall process duration, which provides the opportunity for involved companies to be leaders in electric propulsion systems at European and global level. All of the responders found the participation in the project an interesting experience while working with new concepts and collaborating with capable partners. Additionally, the need to assign more clear roles and responsibilities in such a complicated project that includes construction of major components was highlighted. A partner with relevant technical knowledge that can have the role of the "integrator" is highly recommended. Technological development often drives innovation, which in turn is often the driver for governmental regulatory changes. The future of technical solutions, creation of jobs and services within our society may by constrained by the lack of a suitable environment. There is a consensus among project partners to continue their attempts towards electric propulsion of ferries to conduct in-depth research as well as to improve the regulatory framework. As such, The E-ferry project has great potential to be the innovative catalyst that is needed to accelerate and drive acceptance of utilizing innovative methods in future electric ferries.

5.5.3 KPI – societal evaluation

The main indicators on which the E-ferry societal evaluation has been based, and which the above analysis and discussion have evaluated, are as follows:

***Table 56*: Indicators for the assessment of the societal impact of E-Ferry**

	Indicator	Type of data	Outcome

[29] *Mass customization, is the use of flexible computer-aided manufacturing systems to produce custom output. Such systems combine the low unit costs of mass production processes with the flexibility of individual customization.*

Creation of new jobs			
1	Number of new production jobs created	Qualitative data covered through questionnaire	All of the partners (100%) answered that new jobs will be created. 4 new jobs for 1 respondent
2	Number of new assembly jobs created		All of the partners (100%) answered that new jobs will be created. 3 new jobs for 1 respondent
3	Number of new jobs created in relation to CFR material		All of the partners (100%) answered that new jobs will be created.
4	Number of new jobs related to the battery and battery assembly		All of the partners (100%) answered that new jobs will be created. 2 new jobs for 1 respondent
Elimination of jobs			
5	Number of jobs lost due to lower manning requirements	Qualitative data covered through questionnaire and from economical evalution	1-4
6	Number of jobs lost in relation to the building of conventional ferries		Zero

6 Results and conclusions

In relation to the E-ferry prototype performance, we conclude that the E-ferry – with some smaller variations both negative and positive – has met the initially defined requirements. Though the E-ferry – like most ferries of its size and type – is about 5% heavier than originally projected, due in particular to design changes to the battery and charging system, this has not affected the average energy consumption in any measurable way. In fact, at an average consumption of 1600 kWh per return trip, the E-ferry performs slightly better on this feature, presumably due to exceptionally good hull-design, with a lower resistance than projected as a consequence. Moreover, as the additional weight is unevenly distributed, with a resulting negative trim, the energy consumption is not negatively affected by increased load on the car deck, where it is usually the case that heavier loads will lead to higher energy consumption for a vessel. The low average energy consumption per trip, in combination with a battery capacity available of above 3.8 MWh and a charging effect of 4MW, has proven that the E-ferry prototype is – in technical terms - a valid commercial alternative to traditional diesel- and diesel-electric propelled ferries, as the E-ferry prototype, as built, can be – and has been – put into commercial operation on equal terms to its equivalent diesel-propelled alternatives, while also taking operational aspects such as connection to other forms of transport, accumulated delay and weather conditions into account.

The evaluation has also concluded that the economic grounds for electrification are also there, i.e. that the E-ferry prototype is a valid commercial alternative from a purely economic aspect. Thus, while E-ferries in general, and the E-ferry prototype in particular, have higher construction costs than their conventional counterparts, the operational costs, especially those dedicated to energy/fuel, are significantly lower for fully electric vessels, so that the higher investments costs are in fact paid out after 5-8 years of operation, compared to best available technology for diesel-electric propulsion and when taking into account the potential necessity of replacing the battery pack twice over the vessel's total lifetime. As also indicated in the economical evaluation, while battery systems have been a major cost contributor to the E-ferry prototype's initial investment costs, the steady decrease in cost of €/kWh even for marine applications makes the perspective for fully electric vessels even better in the future. Another main contributor to the total cost of the E-ferry prototype is the electrical infrastructure and charging system, which for future E-ferries should preferably be constructed on different owner-terms, which would lead not only to lower one-time investment costs, but also to saving on the cost per kWh for the charged electricity. With these measures taken, it has been predicted that a future fully electric E-ferry (series 3) would in fact break even when compared to the diesel-electric best alternative within 4 years of operation, after which the operational savings of the E-ferry would apply year for year. In total, life-time investment, or cost-over-total-lifetime has thus, for instance, been estimated at 52 million Euro for best diesel-electric alternative, 50 million Euro for the E-ferry prototype and 46 million Euro for an E-ferry series no 3.

The economic benefits over time of going fully electric does not take into consideration any future requirements for low-emission vessels, including potential fees or quotas for e.g. the emission of CO_2. Thus, the environmental evaluation of the E-ferry prototype is based exclusively on the value for the environment, e.g. the reduction in emission of greenhouse gasses and particular matter. In local terms, i.e. in the area of operation, the E-ferry prototype of course presents a 100% reduction of all emissions, given that there is no combustion onboard (or in the harbours). Compared to best technological alternative, it is estimated that the E-ferry saves the environment 2.520 tons of CO_2, 14,3 tons of NO_x, 1,5 tons of So2, 1,8 tons of CO and half a ton of particulate matter. Compared to an older, existing ferry of similar type, the savings are of course even bigger, at close to 4000 tons of CO_2, 70,8 tons of Nox, 2,4 tons of So2, 3,1 tons of CO and 1,4 tons of Particulate matter. These savings are contingent on the E-ferry using so-called green electricity, i.e. electricity produced by clean sources such a wind and sun. If the E-ferry by contrast would be using electricity from the standard Danish grid mix, savings could still be significant compared to the other alternatives, but the E-ferry could no longer be claimed to be entirely emission free in operation. In terms of environmental impact, Life-cycle-analysis also shows that even when taking into consideration the resources and raw materials needed for producing batteries, the E-ferry prototype overall fares significantly better than its alternatives. For instance, the CO_2emissions estimated to be a result of the battery production (215-430 tons) equals about 3 months operation worth of emission from best available technology, i.e. a diesel-electric ferry.

The environmental benefits are also highly rated by the E-ferry prototype's passengers, who overall report that they are either 'extremely satisfied' or 'very satisfied' with the E-ferry prototype in operation. Alongside a high appreciation of the environmental friendliness of the E-ferry prototype, passengers also rate the much more silent operation and noise level highly, just as safety, comfort and travel time (reduced by more than 20%) is either 'extremely satisfying' or 'very satisfying'. That passengers in this way highlight the importance that electrification has for their transport habits also support the overall evaluation from the partners of the E-ferry project, who all expect an increase in jobs and revenue, both from their involvement in the E-ferry project, and from future marine electrification projects more generally.