Part 02: A closer look at the economic, environmental and technical aspects of the E-ferry, and at passenger satisfaction and industry perspectives

1 The economy of sailing fully electric

Fully electric ferries are more economical than traditional diesel ferries

Remarkably, results from the evaluation show that the higher investment costs for building fully electric are in fact already compensated for after just 4-8 years of operation, even when taking into account the cost of the charging station and the potential necessity for replacing the battery pack twice over the vessel's total lifetime. This means that the higher investment costs are paid for early and for the remainder of the ferry's 30-year lifetime, the operator will save between 24% and 36% in operating cost, compared to operating a diesel or diesel-electric ferry.

Table 1.1: Summary of operational costs for the four vessels compared

Vessel	Total costs/year (5 trips/day - 360 days/year) (€)
E-ferry prototype	1.713.669,6
E-ferry series	1.713.669,6
New diesel-electric ferry	2.255.582,1
Existing diesel ferry	2.689.587

Savings from operational cost mainly originate from much lower energy cost due to the better overall energy efficiency of the fully electrical battery drive train (average energy prices of electricity and bunker fuel respectively during the demonstration period for Ellen were very close to 5-year averages for both). Other important savings were achieved via crew cost, as the E-ferry is approved to sail without a marine engineer. Instead a service engineer takes care of running maintenance – maintenance that is less demanding with the simplicity and few moving parts of the battery drive train compared to fossil fuel engines. Automation also plays a role for operational cost savings especially when compared to the existing diesel ferry also operated by the Municipality operator, used as the second peer in the analysis.

The analysis also concludes that a change in the ownership structure of the charging station, compared to the prototype arrangement in Søby, could bring cost parity further forward to only 4 years. The transformer station is not owned by the E-ferrry operator, but in the case of Ellen the evaluation shows that it would have been better, economically, for the operator to build and operate the transformer station. This is due to large savings in the one-time connection fee for the charging station according to Danish grid regulations and also due to savings in the customer grid-tariffs on a running basis when taking ownership of this local part of infrastructure.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 636027

Table 1.2 Summary of construction costs with ownership of 10kVA grid transformer for the E-ferry series 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	13.250.432	1.857.575	n/a	**16.254.746**
New diesel-electric	13.000.000	n/a	n/a	**14.146.739**
Existing diesel ferry	**12.855.657**	n/a	n/a	n/a

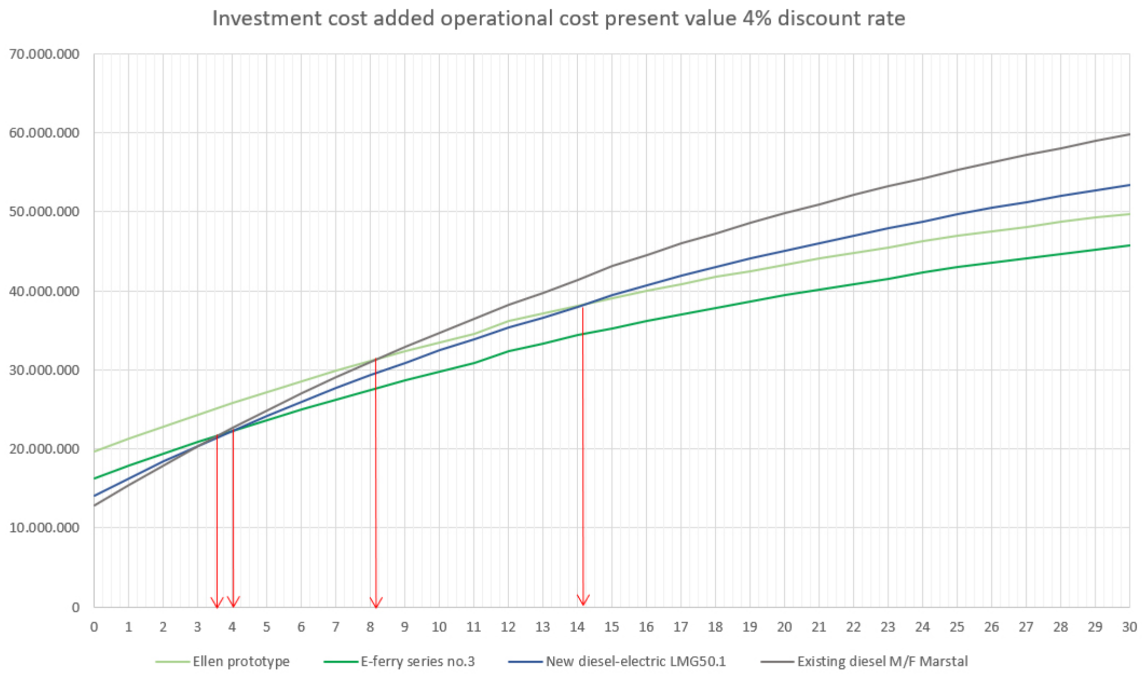

Figure 1.1: Total investment cost including transformer and high voltage infrastructure and operational cost added over a 30-year life span for each of the four vessels. Cost parity is illustrated by the red arrows.

E-technology is constantly becoming cheaper

The battery systems have been a major contributor to the E-ferry prototype's initial investment costs, but the decrease in cost has more than halved the price in the project period. The cost of building an E-ferry series vessel in 2020 with current battery prices compared to the prototype cost incurred by the E-ferry partners can be seen in table 1.2 above. This makes the perspective for fully electric vessels even better in the future. Another main contributor to the total cost of the E-ferry prototype has been the electrical infrastructure and charging system as discussed above. However, in the future charging systems can be expected to be installed in some ports as part of the common infrastructure. At the same time standardization efforts are being exercised already and economies of scale start to apply as environmental requirements dictate the transition away from fossil fuels.

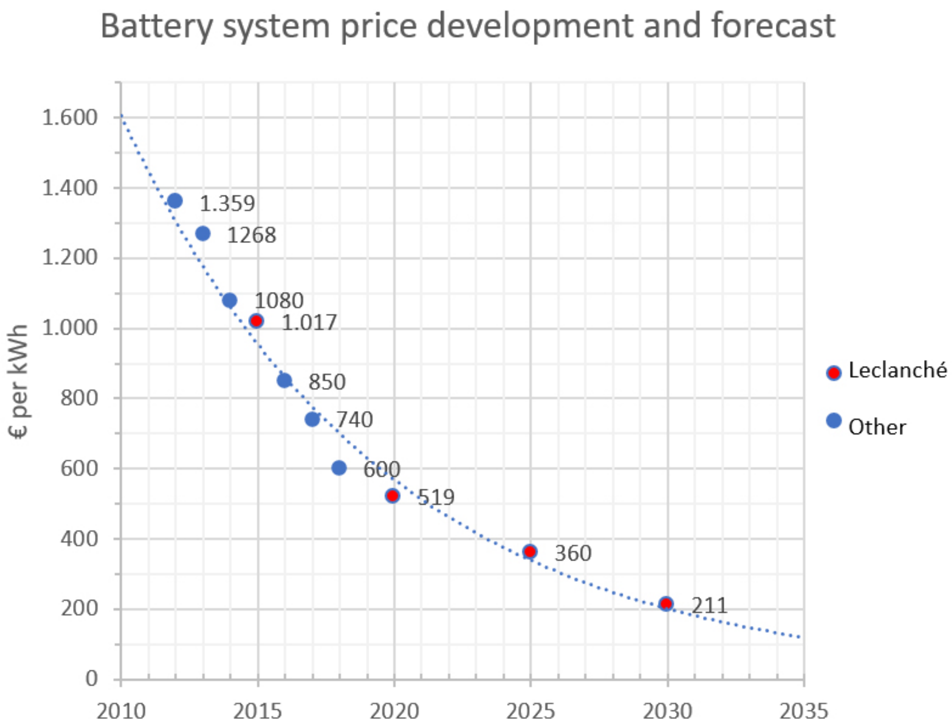

Figure 1.2: Compilation of battery pack price development data for maritime application gathered by Marstal Navigationsskole combined with estimates and realised prices from Leclanché.

The cost of batteries and battery replacement is no longer the main cost driver of fully electric operation. Instead emphasis should be put to the cost of the charging system and grid infrastructure as well as other parts of the drive train such as power electronics for marine application of batteries, inverters, breakers, sensors, cabling etc.

2 The environmental impact of sailing fully electric

One of the most important goals, if not the single most important one, when deciding to built the E-Ferry was to develop the most environmental ferry prototype ever seen, to contribute to tackling climate change by avoiding environmental pollution from emissions of greenhouse gasses and particulate matter. It is now safe to say, that the E-Ferry reduces pollution significantly in comparison to traditional ferry operations.

Based on the Life Cycle Analysis (LCA) that was conducted during E-ferry evaluation, it can be seen that the difference between a fully electric propulsion system on the one hand, and, respectively a conventional diesel vessel or a diesel-electric vessel on the other hand, is significant when considering the overall environmental impact over a ferry's lifetime, regardless if the E-ferry prototype is operating with electricity from the Danish mixed grid or with green energy sourced only from wind energy. This is also the case when taking into consideration the mineral resources (Cobolt, Nickel and Mangan in particular) used for the E-ferry's G/NMC batteries, as well as the resources employed to produce the batteries. The overall conclusion of the LCA is illustrated in Figure 2.1 below. (Lower numbers +/- are better, they signify less environmental impact)

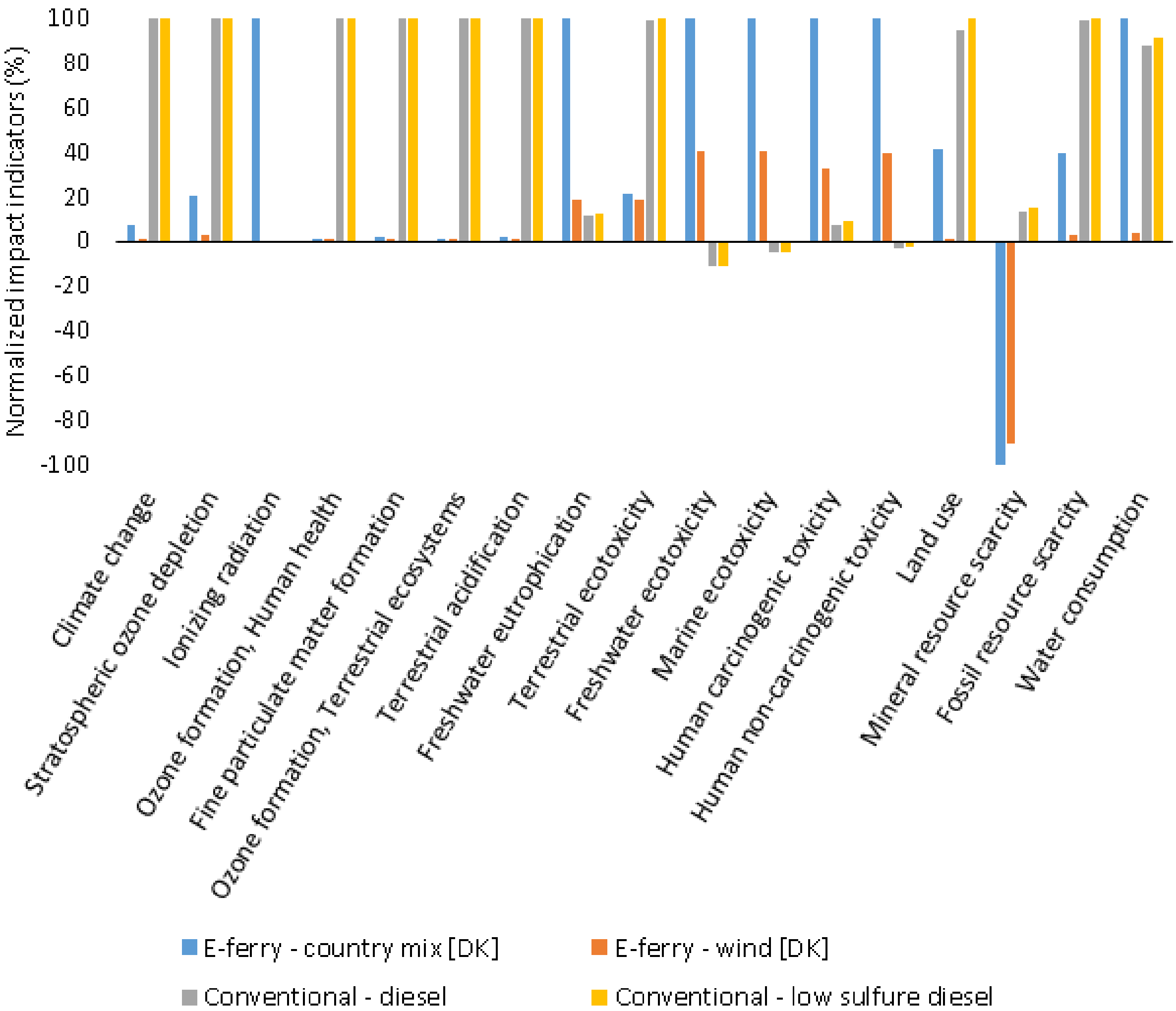

Figure 2.1: Conclusion from Life Cycle analysis of three different vessels

The LCA study is based on a cradle-to-grave approach, taking all stages of the process into account. Overall, the E-Ferry prototype performs better than conventional ferries, whether supplied with an electricity mix from the Danish grid or with electricity coming exclusively from wind energy.

Operational evaluation of the environmental impact

The E-ferry operator has 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 includes about 40-50% electricity generated from fossil fuels (oil, coal and natural gas). 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 green certificates correspond to extra payments to renewable energy producers who put up new supply of wind, solar or hydro power to the grid.

In order to assess the environmental friendliness of the E-Ferry, three different calculations on the topic of emissions are presented in Table 2.1.

Firstly, the emissions savings of the E-ferry prototype when operated with green electricity only, compared to when operated with electricity from the standard Danish grid mix of 2019.

Secondly and thirdly, the green electricity savings of the E-ferry as currently operated compared to two alternative vessels; a diesel-electric and a conventional ferry. Savings are per year. The emission factors used for these calculations are from Energinet Miljødeklaration 2019, Kristensen 2012, and Wismann/Miljøstyrelsen 2000.

Table 2.1: ***Emission savings from one year of operation with E-ferry prototype compared to other modes of operation.***

Emission savings per year	CO2	NOx	SO2	CO	PM10
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	2.520 tons	14.330 kg	1.550 kg	1.791 kg	542 kg
E-ferry versus existing diesel tier I ferry	3.888 tons	70.797 kg	2.403 kg	3.218 kg	1.442 kg

In other words, compared to the best technological alternative (a newbuilt tier III diesel-electric), it is estimated that the E-ferry saves the environment from 2.520 tons of CO_2, 14,3 tons of NOx, 1,5 tons of SO_2, 1,8 tons of CO and half a ton of particulate matter, using 'green' electricity. Compared to an older, existing ferry of similar type, the savings are even bigger, at close to 4000 tons of CO_2, 70,8 tons of NOx, 2,4 tons of SO_2, 3,1 tons of CO and 1,4 tons of particulate matter.

If the E-ferry was using electricity from the standard Danish grid mix, savings would still be significant compared to the other alternatives. In terms of the overall environmental impact, the life-cycle-analysis shows that even when taking into consideration the resources needed for producing batteries, the E-ferry prototype overall fares significantly better than its alternatives. For instance, the CO_2 emissions estimated to be a result of the battery production (215-430 tons) equals about 3 months operation worth of emission from the best available non-fully electric alternative, i.e. a modern diesel-electric ferry.

3 The technical aspects of the E-ferry

Energy efficiency and consumption

The energy efficiency of the total electrical system is 85 % grid-to-propeller. This is more than twice as high as the efficiency of a typical diesel ferry (tank-to-propeller). At an average consumption of 1600 kWh per return trip used from batteries, the E-ferry performs slightly better than had been projected in preliminary studies. If adding the loss from grid to battery the consumption is around 1740 kWh per return trip. The low average energy consumption per trip, in combination with an available battery capacity of more than 3.8 MWh and a fast charger (4 MW peak charge), has proven that the E-ferry prototype is a valid commercial alternative to traditional diesel- and diesel-electric propelled ferries also on ferry routes of longer distances and a high frequency of daily connections.

Table 3.1: ***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

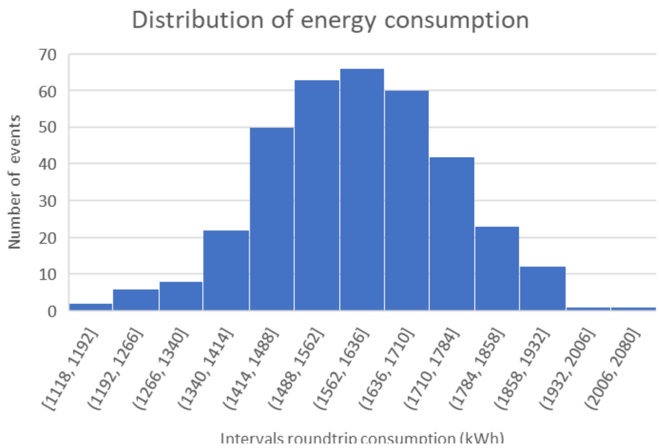

Figure 3.1: Distribution of energy consumption variation per roundtrip from August 2019 to March 2020.

Performance and charging

The demonstration ferry Ellen has been performing five return trips daily with high reliability and regularity using its higher speed than its predessesors to compensate for charging breaks of 20-40 minutes during port stays in Søby. The E-ferry only charges at one of the endpoints after sailing 22 nautical miles. More important for the operator, it has been possible for the operator to keep these five return trips within one 14-hour crew shift only, taking into account rest-hour regulation and crew cost optimisation. The ferry will have its night stay in the port of Søby charging for the next day but can perform up to 7 return trips in the peak season if needed and another crew shift is added to the daily schedule.

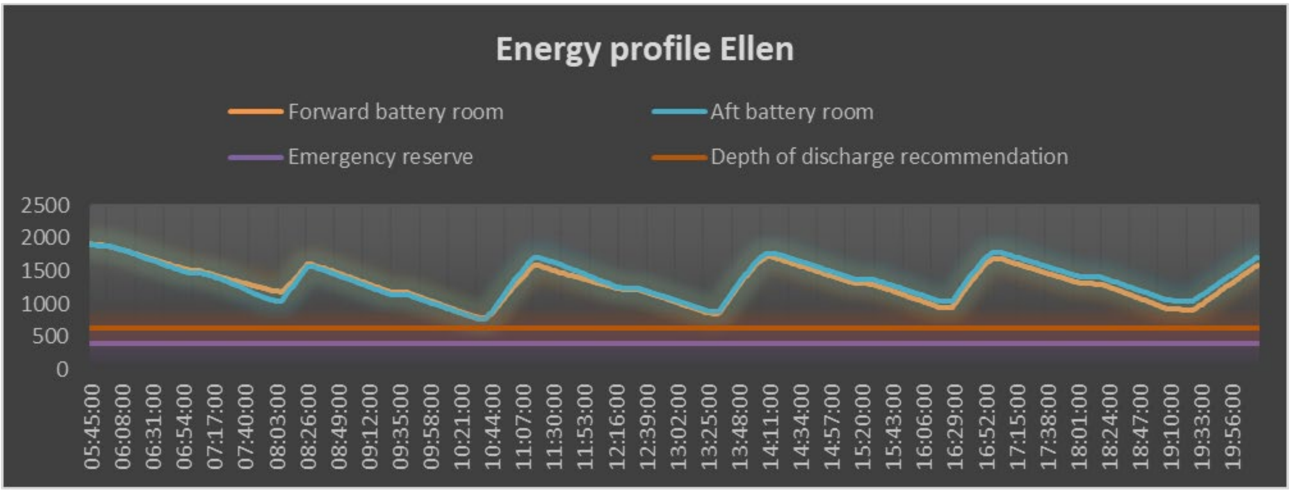

Figure 3.2: Energy profile during typical day of operation with the E-ferry in demonstration period.

Charging speed is vital to fully battery operated vessels. The charging plug developed by Finnish company Mobimar and the charging station developed by Danish Danfoss Editron can deliver up to 4 MW of power during port stays. The plug is located on the ferry ramp making the system very reliable also during changes in water level. Several extremes has been tested successfully during the demonstration period.

Figure 3.3: Charging system on the ferry ramp (green box to the right).

The 4 MW peak effect entails that the maximum transferred energy from shore to batteries would be 66.6 kWh per minute, not accounting for any losses that occur from grid to batteries during the charging. As illustrated in Figure 3.4 below, which provides the energy transfer per minute during four charging breaks of April 24, 2020, the actual maximum energy transferred is closer to 60 kWh.

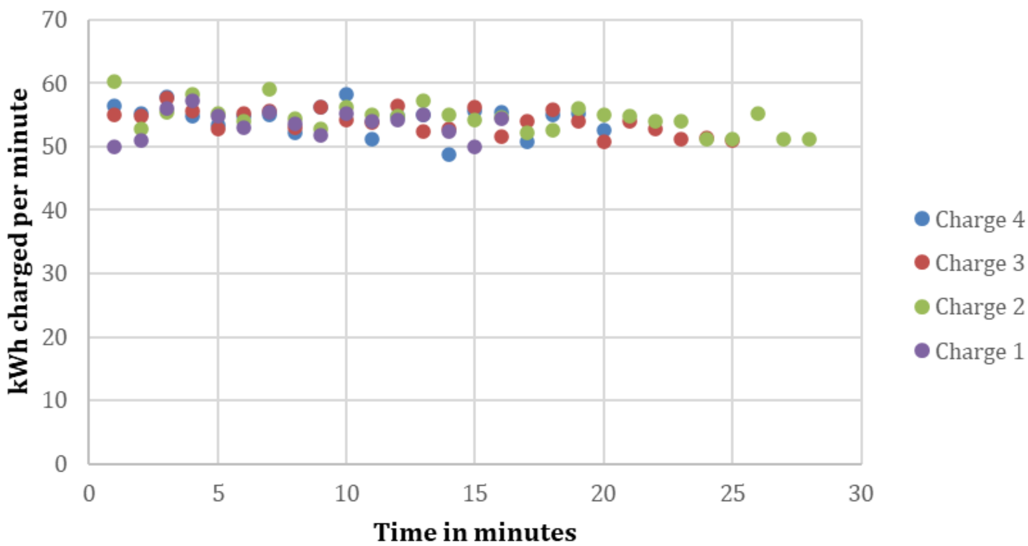

Figure 3.4: Charged kWh per minute, four charging breaks on April 24, 2020

The evaluation analysis confirms the expected dependence of battery State of Charge (SoC) to charging speed. Thus up to around 65% SoC batteries will request almost full charging speed. From 65% to around 80% SoC charging speed decreases slightly and from 80% to 90% SoC drops significantly to half. Normally the battery pack is kept outside nominal capacities of close to 100% to avoid degradation on its lithium-ion chemistry.

Battery balancing has been a large part of the demonstration period research. Aligning the battery modules of the 20 battery strings to optimize performance is mostly done automatically during the night by the battery management system and power management system. During the docking in November 2019 a number of changes and optimisations were done on the battery software and hardware which gave measurable improvements to the E-ferry performance afterwards, lasting for the rest of the demonstration period. Balancing and "fine tuning" new big battery systems like the one of the E-ferry can take a long time, several months according to the experience from the demonstration period.

Hydrodynamic performance and impacts of waves, weather and loading condition

Extra sensor systems have been build into the E-ferry prototype Ellen to measure and evaluate a number of conditional parameters such as impact from wind and waves, draft, temperature, loading conditions etc. More detailed results can be found in the full evaluation report. The hydrodynamical wave system generated from the speed of the vessel itself is very low, as predicted by the CFD calculations and simulations in the design phase. This is further supported by the low energy consumption measured in the demonstration period, even at relatively high speeds. The hull resistance is low and energy demand for propulsion were found to be more than 50% higher for the existing diesel peer (at same speed used for the analysis). This vessel was built in 1999 and is also operated by the Municipality of Ærø. The new diesel-electric vessel which the E-ferry is also compared to in the analysis is assumed to have the same hull shape as the E-ferry and therefore energy demand for propulsion is the same. However, better energy efficiency of the battery drive train, delivering the propulsion power, will add savings also compared to the new diesel-electric ferry.

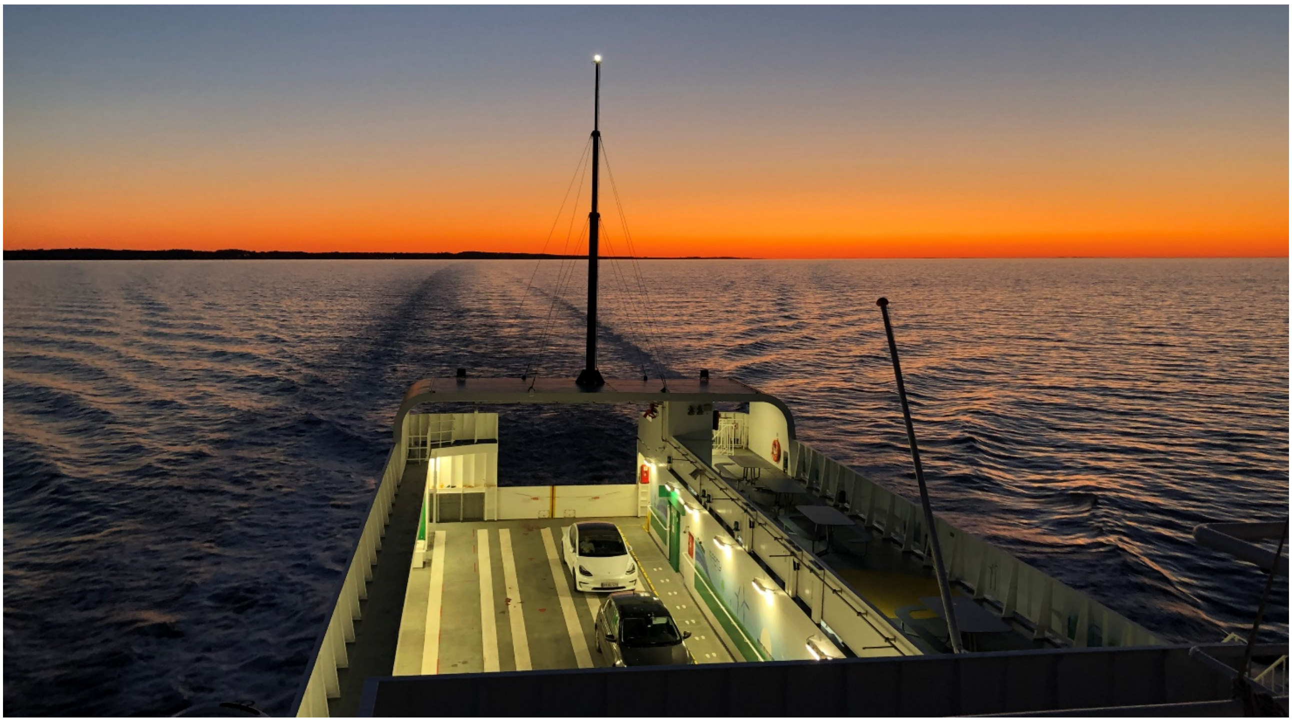

Figure 3.5: Divergent and transverse wave pattern from E-ferry Ellen at 12,5 knot sea speed in calm weather conditions 19th of April 2020. Photo: Henrik Hagbarth Mikkelsen.

The loading condition of Ellen also have an impact on energy demand. However, due to a higher weight than expected, the forward battery room design trim ended up being a little too much "on the nose", hence some ballasting in the aft ship has showed to be optimal in normal operation during the demonstration period. When heavy loads (trucks) are loaded, they are placed aft so ballast can be reduced. Therefore evaluation analysis have not been able to show any significant increase in propulsion consumption when Ellen is heavily loaded.

Weather conditions do impact the energy demand of the E-ferry as for all other ferries. The off-set by head wind and head sea though, will typically be gained back on the returning leg where these effects support the propulsion.

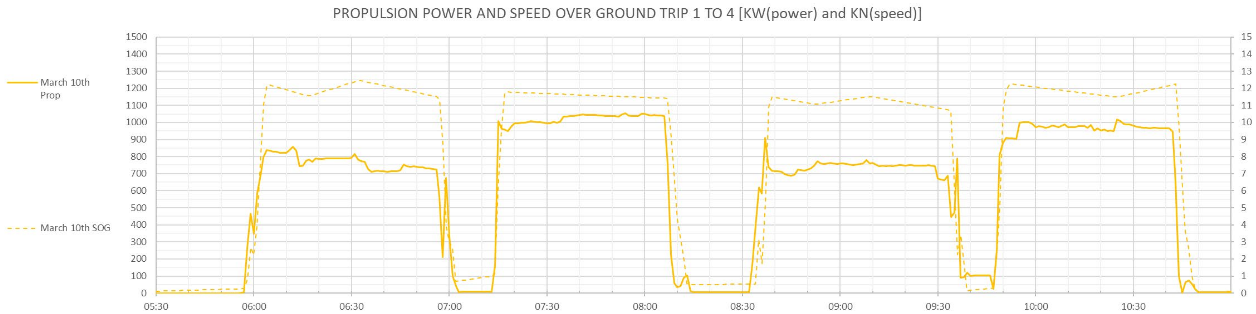

Figure 3.6: Propulsion Power (left axis) and Speed Over Ground (right axis) for first and second roundtrip from the windy day of 10th of March 2020. Speed is almost the same both ways as wind helps respectively counteracts the forward speed of the vessel

4 Passenger satisfaction and perspectives for the industry

Apart from the indisputable benefits from an environmental, financial and technological point of view, significant social benefits also accrue from the development and operation of the E-Ferry prototype.

Passenger Satisfaction

During the demonstration period, all passengers rated their level of satisfaction with the E-ferry overall as either ‘very satisfied’ (41.3%), or ‘extremely satisfied’ (45%). All passengers participating in the evaluation were already aware that the vessel they were onboard was fully electric and had first heard about the E-ferry before, either from newspapers, from friends or relatives, or from other sources.

The E-ferry was evaluated positively on areas such as Safety, Comfort, Travel time, Noise level and – not surprisingly – Environmental friendliness; in all these categories, the majority of passengers were either ‘Very satisfied’ or ‘Extremely satisfied’. For four of these categories, passengers rate these higher when comparing to their experience with other ferries, i.e. they evaluate that the E-ferry is more environmentally friendly, has a shorter travel time, better comfort and less noise. Moreover, passengers confirmed that their expectations about general safety on board the E-ferry were met and that they were satisfied or even extremely satisfied with that.

When asked about how the implementation of the E-ferry prototype in operation would influence their travel and transportation patterns, 50% of the passengers responded that E-ferry operation is likely to increase the frequency of their transportation. 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, 57% of the passengers listed the frequency of the operation as their main motivation for using the ferry service more often than at present.

Alongside a high appreciation of the environmental friendliness of the E-ferry prototype, passengers also highly rate the much less noisy and smoggy sailing experience, just as safety, comfort and travel time (reduced by more than 20%) was deemed 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, which is explained in the following section.

Perspectives for the industry

All of the companies involved in the development of the E-Ferry stated clearly that they expect new jobs 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 that the introduction of new technologies can lead to loss of jobs and reduced wages (Sachs and Kotlikoff 2012), none of the companies mentioned that is the case within their organizations. New job roles to be created relate to new building departments, installation of Battery/DC systems on electric ships (hybrid), installations of power systems and battery management, project managers, lead engineers, project engineers, automation engineers and technical sales engineers for the marine business line..

Companies also found that the new jobs to be created are likely to require an increased number of specialists (85%). On the other hand, 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. See Figure 4.1 below:

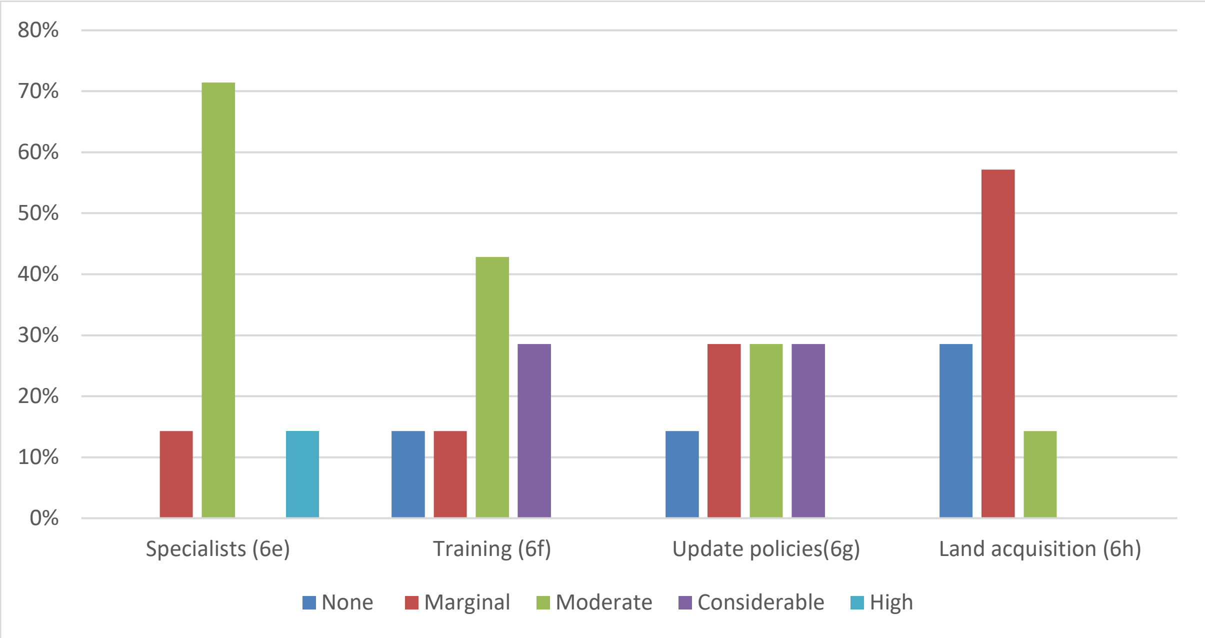

Figure 4.1: Increased number of professional specialists (6e); Training of existing employees (6f); Updating job regulations and policies (6g); Acquisition of additional land to expand company activities (6h)

In conclusion, the companies involved in the development of the E-ferry prototype find that working on an innovative project like the E-ferry 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 companies 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.

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 regulatory 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.