Design Analysis

Fully electrical lightweight ferries - Technical Paper

Green Ferry Vision Partnership

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1 Introduction

The use of electricity charged on batteries for the propulsion of short sea ferries will introduce a shift of paradigm for the operational setup in ferry transport on shorter distances. Replacing fossil fuels and conventional diesel generator sets with pure electrical drive trains will increase total energy efficiency dramatically.

Higher efficiency
When producing the electricity ashore economies of scale will, regardless of the source of energy, be a competitive advantage to producing the propulsion energy on board the ship. The loss of energy from storage on batteries is, with modern lithium ion battery technology, almost negligible being in the range of 4-8 percent. At the same time propulsion efficiency is increased significantly as the need overall energy efficiency ratio is much higher than for diesel or diesel-electrical drive trains. In addition the electrical motor provides full torque also at very low propeller revolutions (RPM) increasing manoeuvrability for the ferry.

Operational setup
The use of shore produced electricity has a huge impact on how the ferry routes are operated and how schedules are optimized. Example given, the conventional approach to shorten turnaround time in port and go for economies of scale through larger ships will not always be a valid approach for the e-ferry as to the need for sufficient charging time alongside. The derived effect of this extra time in port is a need for more but smaller ferries compensating for the extra idle time in port, thus producing a better departure frequency instead.

Challenges
There are a number of challenges to the introduction of pure electrically driven ferries both in terms of legislation and in terms of construction and operational efficiency. Present regulations for energy taxes and the technical construction of ferries have not foreseen this paradigm shift to electrical propulsion and the need for lightweight electrical equipment and Carbon Fiber Reinforced CFR composite materials in particular.

Also the ambiguous question of manning is still to be investigated as for example the engine room is almost eliminated and no fuel oil is on board; what would be the requirement for an engineer?

Figure 1.1 The innovation S-curves of ship propulsion adapted from Everett Rogers, Diffusion of Innovations

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Therefore legislation in general is a hindrance creating paradoxes not promoting a more environmentally sustainable ferry operation. E.g. hydro carbon fuels for ships are exempted for all taxes in many EU countries while electricity is heavily taxed. These paradoxes and challenges will be dealt with mostly in other parts of the feasibility study. However preliminary conclusions from these other parts have been vital to support the design analysis.

**Philosophy of cost**

The return on investment changing to this new paradigm of e-ferry operation is a classic case of higher investment cost against lower running cost. The Green Ferry Vision feasibility study is trying to assess exactly this dilemma of up front finance of assets against future cost savings on running cost being energy, manning, maintenance and, not to forget, environmental conditions.

The lack of less tangible socio-economic costs in the investment budgets of ship-owners result in a bias towards the existing and conventional propulsion regimes. In other words the payback time of the e-ferry investment will be affected positively when, new and less biased legislation hopefully is introduced in the future. Therefore the this discussion needs to be supported by as detailed technical data as possible and the Green Ferry Vision feasibility study will be part of providing such preliminary data.

**Status**

Fortunately, despite of the flaws in maritime environmental regulations, the feasibility study shows that, already now, in many cases the e-ferry concept will be the most economically attractive choice. This means that the environmental advantages in these cases are given us for free, truly a rare thing in operation of businesses.

The next step will be to prove the findings form the Work Packages of the feasibility study for a new innovative E-ferry concept in a full scale prototype test. This work has been going on in parallel with a joint-venture of the partners in the Green Ferry Vision feasibility study and added new international partners in order to define a demonstration project that will lead the way forward for the innovative fully electrical passenger car ferry, the E-ferry, described in this design analysis.

1.1 Purpose and methodology

The purpose of this Work Package 2 & 3 Design Analysis is to describe the design choices made in order to make the vision of the E-ferry concept possible and to evaluate these design choices in a broader context as to the operational challenges of exploiting the new technology and possibilities for battery driven ferries. From a design perspective the following challenges need to be approach;

1. Design of an energy efficient hull form capable of sailing also at shallow water depth with extremely low water resistance in order to increase range for the battery operation.
2. Design of a drive train layout with a battery management system and battery packs sufficient to ensure a complete operational working day for the ferry and at the same time a viable life-span of batteries in terms of recyclers and shelf life.
3. Design of a shore charging connection system and transformer stations to interconnect with public electricity grid capable of very high charging powers in order to minimize charging time during port calls.
4. Design approval of the use of lightweight equipment and materials and especially the fire hazardous concerns in conjunction to use of CFR composites for ship building materials.

**Case study**

The chosen case study of electrical ferry operation to the island of Aeroe in the southern part Denmark will stretch the battery technology to its limit and sailed distance of up to 13 NM would be record breaking for fully electrical ferry operation, not being hybrid diesel-battery or LNG-battery solutions.
Therefore all found design solutions need to be state-of-the-art in order to find the way for the transition into zero emission short sea ferry shipping and to generate a new clean tech maritime industry in Europe.

Findings from the design part of the case study will feed into other parts of the work for electrical ferries both with respect to other Work Packages within the Green Ferry Vision feasibility study but also with respect to the full scale demonstration project seeking financial support from the EU Horizon 2020 call topic MG-4.1-2014: Towards energy efficient and emission free vessels.

*Technical paper*

Methodology in this Work Package 2 & 3 Design Analysis is mostly descriptive illustrating the design choices made during the one-year work programme. The feasibility study is funded partly by the South Danish Forum of Growth (Syddansk Vækstforum) in cooperation with the EU European Regional Development Fund.

This part of the overall feasibility study will focus on the technical aspects whereas both economic aspects as well as environmental and social aspects are discussed based on the findings from all Work Package (WP) in the main report in WP 4, Socio-economic Analysis.

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2 E-ferry design of hull and superstructure

2.1 General arrangement

The E-ferry design aims at supporting and promoting energy efficient, zero greenhouse gas (GHG) emission and air pollution free waterborne transportation for island communities, coastal zones and inland waterways in Europe and beyond. Moreover, the overall objective of E-ferry design is to apply an extremely energy efficient design concept and demonstrate a 100% electric, emission free, medium sized ferry for passengers and cars, trucks and cargo.

It is designed for full-scale operation on longer distances than previously seen (> 5 NM) for electric drive train ferries, i.e. the medium range connections Soeby-Fynshav (10.7 NM) and Soeby-Faaborg (9.6 Nm) in the Danish part of the Baltic Sea connecting the island of Aeroe (Ærø) to the mainland. With shore charging connections in both departure and arrival port it would also be able to cover distances of up to 13 NM which is the distance from Ærøskøbing to Svendborg.

Aside from being 100% powered by electricity, the innovative novelties of the E-ferry design concept and expected impacts perfectly addresses the flaws in current state-of-the-art by demonstrating a vessel concept based on optimised hull-shape and lightweight equipment and the possibility of using CFR composite materials, ensuring energy savings by up to 50% compared to conventional ferries and reduced weight by up to 60% on the parts replaced by composite elements. All CFD calculation with respect to energy requirement for propulsion has though been based on weight of steel and high tension steel where appropriate for hull and superstructure and aluminum for the navigating bridge. The reason for this is that partners wanted to have a viable solution also if CFR composite do not obtain standard approvals within the time of the demonstration project.

This means that the found water resistance calculations could become even lower if partnership successfully gets approvals for partly use of lightweight materials other than aluminum. The great focus to weight issues is double sided. First it is important to compensate for the heavy battery pack of around 50 ton added to the construction, secondly the lighter the ship the less battery capacity is needed due to less draft thus resulting in less energy consumption.

![Figure 2.1 Profile illustration showing the base concept of the E-ferry design. Source: Jens Kristensen Consulting Naval Architects](image)

The base design of the E-ferry is found to be able to serve a wide range of domestic ferry routes for small and medium sized routes. The design is modular in terms of size, as it can be adjusted in length quite easily due the use of standard component for the drive train and ample room for batteries and equipment below car/weather deck as there are no oil tanks or big diesel engine sets needed.
Figure 2.2 General arrangement on decks of base E-ferry concept design. This is suited for small to medium sized routes with a capacity of 25 PCU (Person Car equivalent Units) and 147/98 passengers (summer/winter). Source: Jens Kristensen Consulting Naval Architects.

If extended the ferry will be able of carrying 28 PCU (Person Car equivalent Units) instead and eventually with suspended car decks 36 PCU. Deadweight is as high of 220 ton for the base design which allows for a full load of heavy trucks in the illustration two semitrailers, one truck train with trailer and one single truck.

Initial calculations indicates that hull length can be extended if more capacity is needed actually gaining on energy efficiency. Deadweight will not be limiting a full load of trucks in a longer version extended e.g. 6 or 12 meters. The average cargo weight on the other hand would most likely rise if load factor (ratio of capacity used) is kept constant resulting in a higher energy demand.

Accommodation is situated at the weather deck besides the car deck. Although taking up some space from the car deck this design choice is considered wise if manning requirement should be reduced to three or even two crew members when sailing with less than 99 passengers. The feasibility study has not been able to confirm the future requirement of safe manning document and this will most likely await the real time process of getting a full scale demonstration project into the sea as also labor union and ship owner associations are part of the hearing process in Denmark.
Location of battery packs, switch boards and drive train including 2 x 750 kW electrical motors, gears two propellers and two 250 kW bow thrusters are shown in Figure 2.3. Tanks will mostly be void spaces. Hydraulics will be avoided for bow visor, winches and other equipment and machinery except maybe for the steering gear engine where alternative solutions are still looked into.

The weight of the batteries are around 50 ton wherefore they need to be distributed weight wise both to ensure optimal trim but also to compensate for the unevenly distributed weight of the accommodation and superstructure.

For heating purposes also heat exchangers will be added to the design extracting or delivering heat to and from the sea water depending of the time of season. Heating the ferry in winter time becomes an energy demanding task, as almost no excess heat is produced from the propulsion drive train. Only around 600 kWh per day is emitted from the battery system in full operation. Therefore little ventilation is needed to remove excess heat in summer time. The batteries are not water cooled.

2.2 Design philosophy and safety criteria

Ferries have a long life-time, normally more than 30 years and many more than 40 years. Thus, it is very important to give energy efficiency and maintenance cost a prime focus while designing the ferry. Accordingly, the possible payback time could also be long, overcoming a higher upfront cost within the life-time of the ferry.

Ferry services in Denmark, the EU and around the world are facing challenges such as increasing energy prices, demand for energy efficiency and conversion to renewable sources to provide future answers to affordable, sustainable and emission free ferry transport. These challenges are particularly acute for islands and other isolated communities. Due to the long life-span and since energy efficiency has not been a focus area until recently, many energy inefficient ferries are in operation in Europe. They may advantageously be replaced with new, energy efficient ferries.

Figure 2.4 The hull shape of the E-ferry is inspired by old ferries from the 1930’s to 1960’s but meets the intact and damage stability of today. Source: Jens Kristensen Consulting Naval Architects
The stream lines of the E-ferry is inspired by ferries from the 1930’s to 1960’s where not only capacity and cost but also energy efficiency and speed was in more focus. But the innovative hull design by Jens Kristensen Consulting Naval Architects combines the slim old fashion hull design with modern criteria of stability. Indeed the ferry design meets relevant national and international legislation and requirements (including EU-directive 2009/45/EU and SOLAS). Also the ferry meets very high safety standards (higher than required for category C and D areas) by being meeting the requirements of a two compartment ship meaning that it damage stability wise can survive flooding of two compartments at the same time.

This in combination with the highly redundant electrical drivetrain makes the E-ferry much more safe than existing island ferries e.g. for the island of Aeroe which does not meet same criteria and for example would not meet new wind stability criteria for a full storm. For the E-ferry the low design of superstructure will fully fulfill the wind criteria and at the same time help maneuverability in port in windy conditions.

The choice of placing the passenger saloon/accommodation for the most part on the weather deck is adding safety to the design because most passengers can be evacuated easily via the side doors without severe height differences or long chutes. The layout will help crew assist all passengers during evacuation and also physically disabled passengers will have easy access to life rafts.

2.3 CFD calculations

From the funding from South Danish Forum of Growth (Syddansk Vækstforum) and partnership contributions it has been possible to test the energy performance of the innovative hull design by CFD (Computational Fluid Dynamics) tools at Force Technology in Copenhagen.

The first result have been used for further optimisations and after the delivery of this report a second set of calculations are being performed thus giving the findings from the first report a preliminary status. It is however expected that the result of the second round of CFD calculation will only improve energy efficiency as several minor improvements have been added to the design.

Also the results of the first run of CFD’s has been feeding the electricity balances needed for the design choice of battery capacity, please refer to next chapter. The initial CFD’s were made at a draught of 2.50 meters. The more likely draught when operating with an average cargo load of cars and trucks is below 2.40 thus estimates from this feasibility study can be said to be conservative.

CFD’s are prepared for infinite water depth at Force Technology wherefore the naval architect Claus Nielsen at Jens Kristensen Consulting Naval Architects has prepared a mathematical model correcting energy requirement at lower water depth. This model is of vital importance in order to design the needed drive train and battery pack as most island routes and inland waterways will be sailing through shallow water areas.

As can be seen from the table, CFD’s are calculated for a speed of 14.0 KN the full speed of the vessel is expected to be 14.5 KN at construction draught. Design conditions are based on 49.750 meter length o.a. and beam moulded of 11.6000 meter.

Table 2.1 Calculated (RANS CFD) dynamic trim, sinkage and model resistance extrapolated to full scale using ITTC-57 method. Analysed with a form factor of 1.14 and a correlation allowance factor of 5.35E-04. A negative value of trim corresponds to “bow down” trim. Source: Force Technology
The calculated flow field results in Figure 2.5 show a typical wave pattern and ship flow field with: 1) High pressure in the bow where the flow is slowed down and the bow wave is formed due to stagnation, 2) Low pressure around the shoulders where the flow is accelerated to get around and below the hull, 3) recovery of the pressure and basically constant flow properties along the prismatic section of the hull, 4) decrease of pressure at the aft shoulders, i.e. the region where the hull form start to narrow in towards the stern and the water starts to flow into the wake region and 5) increasing pressure in the stern region and formation of the wake field with lower velocities.

Compared to existing ferries servicing for example Aeroe at lower speeds than 14 KN The E-ferry design performs well in terms of low water resistance which can be seen by the modest height of the ship generated wave system. Still improvements were suggested from the run of CFD calculations of which most have been implemented.
Based on the results of the wave pattern around the fore-body, see Figure 2.6, it is seen that the bow wave is lifted up high into the knuckle line and is believed to create a lot of resistance. The effects of the bulb is believed to be limited, the water surface in front of the bow does not raise up which indicates that the bulb is not working to its optimum, a longer and higher bulb could be recommended. Maybe a trawler like bulb could be taken into consideration, as this is very versatile when it comes to large draft variations.

**Figure 2.7 Free surface elevation at stern from E-ferry. Source: Force Technology.**

In the aft part of the vessel a small stern wave is built up and even with a submerged transom the wave is very small and the resistance contribution is negligible compared with the wave system generated by the bow region. The streamlines and hull pressure generally look smooth.

**Figure 2.8 Streamlines in the stern of the E-ferry design. Source: Force Technology**

The skeg is very nice and very nicely faired into the hull. Like for the rest of the aft hull the streamlines looks very nice with no recirculation to be seen. This means that most of the further optimisation has now been focused on the bow and “shoulders” of the ferry improving performance for this part compared to first CFD calculations. The result of this work is still to be awaited.
Although there will always be room for improvement the CFD indicates an energy efficiency of the E-ferry design far beyond comparable existing Danish island ferries in service. In the illustration below the CFD or if not available test tank photos has been compared from four island ferries;

Figure 2.10 Comparative illustration of four island ferry designs and their wave pattern along the ship side. Please note the higher speed of the E-ferry design. Source: Jens Kristensen Consulting Naval Architects.

Figure 2.11 A comparison of required energy at propeller as a function of speed shows savings of up to 50 per cent at full service speed even though the E-ferry data has been calculated based on higher deadweights.
3 Electrical drive train and batteries

The task of finding the optimal layout and setup for battery capacity has been based on the findings from Chapter 2. Many parameters are needed both from the technical design and from the operational requirements of the route in question for the optimisation of this task. Again the case study of the ferry routes of Aeroe has been used as a basis for design choices but also looking into the overall market potential of found solutions.

3.1 Drive train layout

The fully electrical drive train has been based on Siemens BlueDrive PlusC™ standard designs adapted to ferry operation and requirements of the design described in Chapter 2. The general arrangement or oneline diagram for the drive train can be seen in Figure 3.1 below;

![Figure 3.1 Siemens BlueDrive PlusC drive train for the E-ferry with two separated switch boards and total shore connection capacity of up to 4 MW. Source: Siemens (project partner)](image)

At least two world news can be seen in the oneline diagram from Siemens with the full layout of drive train for the E-ferry. One record is the 2 x 1900 kWh battery packs being the biggest installation in any vessel we know of. Siemens has installed 2.7 MWh batteries for the Scandlines ferry "Prinsesse Benedikte" but for the fully electrical passenger car ferry ZeroCat starting operation in Norway next summer the battery pack is only 1 MWh. This ferry has transit distances much shorter than the ones that the E-ferry concept is targeting.

The second record-breaking feature is the 4 MW shore charging capacity hence high charging power capacities will be a key feature of future transition to electrical

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operation. This is in order to save battery weight and cost and also to save time during port calls although some charging will take place at every call at the shore charging station. Design of the shore charging station is discussed further in next chapter.

The split up of all vital systems in two fully redundant drive trains promotes the argument that no emergency diesel-generator is needed. As for smaller double ender ferries with two similar and redundant engine rooms fore and aft this has been approved of by classification societies and maritime authorities.

A dialog based on same arguments will go on into the next phase of design. Therefore the feasibility study cannot yet answer if this is fully a viable setup. If not the ambition of a fully fossil fuel free vessel cannot be fulfilled. This however does not affect the ambition of a fully electrical drive train during normal operation.

The far distance (two bulkheads) between battery rooms and switchboards reduces likelihood of both battery rooms being flooded or subject to fire at the same time.

### 3.2 Battery system and type

Fire risk of batteries is not as high as often claimed in news headlines of lithium-ion batteries catching fire. The large storage banks of Li-ion batteries will be under a
much stricter control than consumer electronics or even automotive batteries. Battery management systems both within the batteries and in the interface between batteries and main consumers on board will forecast battery temperatures on a continuous basis in order to ensure long battery life-span.

In order to keep warranties these control systems are provided by the battery supplier and Siemens which in term keeps track and delimits the use of batteries if ferry operator tries to handle the battery load too harsh. In return warranty on batteries can be extended as long as 10 years.

Two fires in Tesla cars have been reported but these cells are of another Li-ion type (Li-NCA) than the one chosen for the initial E-ferry design which are Li-NMC are Nickel-Manganese-Cobalt cathode technology.

The Li-ion type battery pack has been certified for marine and offshore applications by DNVGL, ABS (American Bureau of Shipping) and Lloyds Register - three prominent classification societies. The Li-NMC cell type used in the suggested battery type is not coiled but based on flat panels or layers that give optimal control of the temperature inside and therefore is considered to be safer according to the manufacturer. In the research from BCG, depicted in Figure 3.4, Lithium-NMC type batteries are scaled 4 when it comes to safety while in a more recent study by the reputed Navigant Research the Li-NMC-type has been scaled 5 being the safest choice of technology.

However, great uncertainty to the safety of some of the lithium-ion battery types exists, e.g. lithium-LPF has got the highest safety ranking in the BCG study and the lowest in the Navigant Research study. This is because the numbers of required cell connections is weighed differently when it comes to safety. Therefore new chemistries for anodes and cathodes will have a long way to market penetration for both electrical vehicles and maritime transport in order to ensure high safety performance thus batteries of Nickel-Manganese-Cobalt cathodes is considered a good choice for marine application due to its relatively slow reaction to hard charging and discharging. Firefighting if a fire breaks out will be mainly based on water mist but also inert gasses can be of good used in the enclosed spaces of the battery rooms. Still the risk of fire is considered to be much lower than for propulsion with combustion engines and large quantities of fuel oils onboard.
The Li-NMC battery type is capable of high specific powers meaning that it can charge and discharge by several times its capacity which is of great importance to the E-ferry setup because we plan to charge at such high powers. Thus there is also a restraint to going down in battery size coming from the specific power when you introduce very high charging powers.

Battery packs consist of much more than battery cells and e.g. cabling constitutes by a significant part of battery pack weight and can create bottle neck problems affecting performance. Thus battery price is not only related at the Li-ion cells the needed Battery Management Systems (BMS) for the pack will contribute with more than one-third of total price and introduce extremely important features for both safety and performance of batteries and will also introduce quality differences between manufacturers.

In addition, the Power Management System (PMS) or Energy Management System (EMS) of the drive train will also affect overall performance of batteries depending on the Siemens BlueDrive PlusC platform.

Price of battery packs is discussed in Work Package 4 Socio-economic Analysis. This however is an important parameter needed to be considered also for the final choice of battery capacity size.

Depending on the battery capacity, battery quality and battery load the charging recycles cannot last forever. The number of possible recycles depends on how the batteries are treated or managed by the PMS and BMS. For the case study a fully functional life-time of at least ten years has been calculated by the project partner Siemens when determining the needed battery capacity taking into consideration how deep discharged that can be allowed.

This is considered a good compromise. If one wants a longer life span the shelf life of today’s battery technology will start influence the equation harder not allowing the operator to gain the full benefit of purchased batteries although some battery types have an expected shelf life of more than 20 years.

In the feasibility study cost of battery packs will be calculated as part of the new building investment cost including a forecasted price of replacing the battery pack within the economic life-time of the ferry. Naturally great uncertainty about future battery price exists but a conservative estimate has been made.

After ten years the battery pack will need to be renewed or supplemented on a running basis. This means that to ensure the nominal capacity of the battery pack new cells and packs are added as needed and perhaps some of the old ones will be removed if damaged or fully worn out. In theory this process could be ongoing for example for the next ten years. With a life span of a typically ferry of more than 30 years there is no doubt that all batteries will be changed at least once during the economic lifetime of the ferry.
According to Navigant Research it is not likely that any of the upcoming new battery types technologies will change the game and battery industry before 2020 due to the complex process of testing and approval of new battery technology. However after 2020 at least one of three promising technologies could gain a competitive edge. On the horizon is lithium-air being researched by IBM and others. Lithium-sulfur is being researched and developed by Californian battery-tech company PolyPlus and partner Sion Power and German chemical company BASF. The potentially most game-changing technology though is the lithium-water battery.

Although the combination of lithium metal and water sounds a little disturbing to the “amateur” chemist, PolyPlus expect these batteries to exceed 1,000 Wh/kg in specific energy based on their invention of a Protected Lithium Electrode (PLE). The PLE makes lithium metal electrodes compatible with aqueous and aggressive non-aqueous electrolytes. Still none of these new technologies have been included in budgets in Work Package 4.

Used batteries are expected to be sold either for large energy storage facilities on land or for battery packs recycling purposes. In recycling facilities in both the US and Europe lithium, cobalt, nickel, and other metals will be extracted from used lithium-ion batteries. Cobalt, for example, will be refined into high-grade lithium cobalt oxide (LCO) for use in new batteries. This in turn reduces the carbon footprint on the manufacturing side of the battery production equation.

### 3.3 Optimal battery size

The strategic choice of battery capacity on board the E-ferry will depend on many variables and parameters e.g. the features of the ferry service in question. The assessment is complex and an equation of this many variables with inherent high uncertainties, for example to future battery price or future price of fossil fuel, cannot be uniquely solved.

The design work includes the preparation of a model, an electrical balance sheet, for the use of propulsion energy and hotel energy for heating, LED-lighting, navigation equipment etc. The model also needs to include possible charging power from the electricity production and distribution company, South Energy (SE), their role will be discussed further in next chapter. Using this model, an iterative process of obtaining the best possible sailing schedule given the limitation of range and needed charging time for fully electrical ferry operation can be conducted.

When deciding for final battery capacity and needed capacity margins at least the following considerations needs to be addressed;

- **a)** That the total battery capacity installed is sufficient to absorb charging and discharging powers according to the electrical balance sheet, including hotel power, without exceeding recommended temperatures generated within batteries from battery loads as deviations would lead to lower life-span of batteries.
- **b)** That the battery capacity installed is reasonably balanced in relation to the chosen maximal charging powers in port thus higher charging powers will save battery weight but vice versa also result in high investment cost of the shore charging connection station as its price depends mostly on maximum power capacity.
- **c)** That battery capacity installed, at normal daily operation, are not discharged to deep, in the case study not below 40 %, also at worst time of season, ensuring that battery life-span is kept within calculated limits.
- **d)** That the battery capacity installed is big enough to keep the number of daily recycles to a minimum allowing for a long battery life-span.

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e) That the nominal capacity installed is sufficient to compensate for the unavoidable loss of performance within the first 10 years of battery life-time. This can of course also be achieved by installing extra batteries within the first 10 years of life-span but would increase ships weight and maybe also economic performance.

f) That battery capacity installed is designed for a safety margin of at least 10 % or higher for weather adjustments to propulsion energy consumption for the case that a) to e) does not provides such margins.

g) That battery capacity installed is not designed to cope with extreme operational situations encountered only one or two times per year for example the relocation to ship yard for maintenance. Instead mobile power packs should be an option for such planned deviations.

h) Whether the battery pack installed should be increased to exploit the lower night rates of electricity (at certain times spot rates are negative, however price will be added distribution cost also).

For unscheduled deviation g) is of course not an option. In case of emergencies the EU regulation concerning ferry operation for operational areas of category C and D requires only a capacity for the ferry to fight a fire for at least three hours by own means being the emergency fire pumps. Even at the worst time of batteries working day when they are down on 40 % capacity the remaining capacity would be able to run the high pressure fire pumps for more than 10 hours with only one battery set working.

For each of the case study routes an complete operational profile have been prepared taking into account variations in water depth and required transit times and speeds to obtain an hourly ferry service on the routes to and from Aeroe. Only for the longest route from Ærøskøbing to Svendborg such setup could not be achieved resulting instead in a transit time of 65 minutes compared to the present 75 minutes plus.

<table>
<thead>
<tr>
<th>Route: Ærøskøbing - Svendborg</th>
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<tbody>
<tr>
<td><strong>Table 3.1 Spread sheet model of the required energy consumption at propeller for the E-ferry operation, example from part of the route Ærøskøbing to Svendborg.</strong></td>
</tr>
<tr>
<td><strong>Source:</strong> Jens Kristensen Consulting Naval Architects</td>
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</table>

Based on the route profile and hotel power for heating etc. the electric balance sheet for the total operational day for each E-ferry and each route has been prepared in the case study. A philosophy of performing at least three consecutive roundtrips (six single journeys) before any longer charging pauses was found efficient in terms of delimiting
the needed battery capacity. This philosophy is well aligned with concerns to the crew change and minimum/maximum working hours in labor conventions and agreements.

Figure 3.6 Energy balance sheet prepared for E-ferry operation with 7 daily roundtrips. Source: Henrik Hagbarth Mikkelsen, Marstal Navigationsskole

The resulting operational setup for fully electrical E-ferry operation on route length that can be covered within 50 minutes of transit time is shown below in Table 3.2. This allows for a schedule with fix minutes of departure every hour most of the day with only two ferries in operation;

<table>
<thead>
<tr>
<th>Ferry A</th>
<th>Sailing time around 50 minutes. Docking time Aeroe 13 min / mainland 7 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dep. Aeroe</td>
<td>0530 0730 0930 1230 1430 1630 1930</td>
</tr>
<tr>
<td>Dep. mainland</td>
<td>0627 0825 1027 1327 1527 1727 2027</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ferry B</th>
<th>1st crew watch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dep. Aeroe</td>
<td>0630 0830 1030 1330 1530 1730 2130</td>
</tr>
<tr>
<td>Dep. mainland</td>
<td>0727 0927 1127 1427 1627 1827 2227</td>
</tr>
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<table>
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<tr>
<th>2nd crew watch</th>
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</thead>
<tbody>
<tr>
<td>Dep. Aeroe</td>
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<tr>
<td>Dep. mainland</td>
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<table>
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<tr>
<th>3rd crew watch</th>
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</thead>
<tbody>
<tr>
<td>Dep. Aeroe</td>
</tr>
<tr>
<td>Dep. mainland</td>
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</tbody>
</table>

Table 3.2 Schematic sailing schedule with two ferries operating from the same port. This allows for optimal crew shifts to avoid idle time in port with crews onboard. NB: Departure times not final, only shown for illustrating the principles of the plan

The principle schedule shown above will only need three crew watches per day working on two ferries. The first watch is short but covering the minimum workday of 6 hours when half an hour is included before and after sailing for upstart and shut down of vessel. 2nd crew watch will be the longest (12 hours) still shorter than the maximum watch length of 14 hours during normal conditions. The third and last crew watch will be around 10 hours but with changing ship twice within the watch.
4 Shore charging system

4.1 Connecting to the grid

Based on a 4 MW charging station situated on the Aeroe side of routes only and the suggested schedules of Chapter 3 the optimal battery capacity of most routes have been found to be around 3.8 MWh.

The charging power of 4 MW is simply found by looking at both the supply and demand side of technical installations. SE is capable of providing such energies by only minor adaptions to their systems on Aeroe but still transformations from the 1950’s needs to be updated in Søby. A new 10 kV cable will be distributing power to the ferry harbors in question.

The reason why charging stations will only be situated on Aeroe is that all ferries are spending the night here. For the case study route from Marstal to Rudkøbing energy consumption to obtain a transit time of around 50 minutes is too high and therefore shore charging connections are needed in both Marstal and Rudkøbing. These however are quite expensive as a one-time fee regulated by State is to be paid of 1672 DKK or 224 € per kW peak power capacity needed.

This amounts to almost 900,000 € per charging station but two E-ferries will be able to share these station with no added price. The one-time fee could be replaced by an installation cost based approach instead if an agreement to decouple the transformer station when grid peaks makes this favorable for the power distribution company. The decoupling will be a matter of very short periods of seconds or a few minutes when production capacity is challenged by e.g. sudden changes in the weather pattern and electricity from wind turbines.

Such short periods of decoupling sound disturbing if the E-ferry would be docking at the same time but charge depth on the batteries will during normal daily operation not be below 40 % leaving room for a few per cent extra. It will not influence the lifespan of battery packs if decoupling incidents are not too frequent.

The transformation of voltage down to the needed 690 V for the battery packs is delivered on the shore and it is suggested that SE is paid to do this at a running cost of 4.03 € per MWh. Having the competences and standby crew on alert outsourcing of this transformation would be the best choice for most ferry operators thus they do not have an engineer anymore if they are running fully electrical ferries only.

4.2 Shore charging connection

The low voltage of only 690 V and the high power of up to 4,000 kW results in currents of staggering 6 kA which put stress to the shore connection. The requirements for such “plug” are comprehensive ranging from safety to durability at all tides and weather conditions. Also the connections should preferably be automated and get into contact as soon as E-ferries arrive to the ferry berth in order to transfer as much energy as possible to the batteries for propulsion.

Two different systems are being developed one with a plug system that can be elevated to align with plug onboard and another more innovative using a pantograph as known from the top of electrical locomotives and trains (the antenna that has continuous contact to the overhead power line hanging over the track). The latter system would be tilted horizontally and placed ashore allowing the pantograph bar to make contact with the four electric conductors onboard being 4 rails protected by a climate shield toward wind and rain.

For the Norwegian electric ferry “Ampere” ordered by Norled the plug solution has been chosen. Charging power though will only be around 1,000 kW in the small cities of Oppedal and Lavik where the ferry will cross Sognefjorden on a short distance trip.
In addition an automated mooring system is needed in order to bring down manning costs. Here the Cavotech Moormaster system or similar would be suitable. However a possibility would also be to combine these features and the shore charging connection. This however has not been part of the feasibility study to investigate further.

Both systems must be able of adjusting to shifting tides and the unavoidably movements of the E-ferry in port. Therefore rails (conductors) on the ships side in case of a pantograph solution must be long enough to adjust for such vertical movement.

Figure 4.1 Cavotech Moormaster system in the ferry port of Spodsbjerg. Photo: Henrik Hagbarth Mikkelsen

Figure 4.2 Vertical movement of E-ferry during tide and variations in ships draught.
5 Use of CFR composites

If the E-ferry should serve as an SOLAS approved ferry capable of export to all ferry markets with no or only little need for modifications to national legislation then it must obtain approval of the use of carbon fiber reinforced (CFR) composite modules in the E-ferry’s superstructure according to SOLAS Chapter II-2 (Part F) regulation 17 and EU Directive 2002/25/EC.

In the Horizon 2020 E-ferry demonstration project the ambition is to achieve at least some initial approvals according to mentioned regulation through concept, material or fire testing using future guidelines from the Danish KOMPAS-project. The project partner of DBI (Danish Institute of Fire and Security Technology) will be an important partner to disseminate the result of the KOMPAS project to the E-ferry design process.

The concept ferry has been designed using a light weight approach to all aspects of the design including machinery, equipment and a simple hull structure construction. However the approval of carbon composite materials for the newbuilding is still not resolved. Therefore weight of the concept ferry was calculated conservatively using steel and high-tension steel weights where relevant for hull and superstructure.

Thus introduction of carbon composite materials in the newbuilding will allow for further weight savings and higher energy efficiency compared to the found numbers from the first round of CFD calculations. In order to estimate the magnitude of such extra weight reductions the following rule of thumb has been applied:

The immersion weight per cm is approximately 5 ton when in the neighborhood of the construction draft of 2.34 m.

In the draft to power analysis, see Figure 5.1, needed power to obtain 14.5 KN speed at various drafts has been deducted.

By combining the immersion weight of 5 ton/cm and the found power graph it can be derived that power savings per ton reduced weight is approximately 2 kW at 95 % engine load.

Total weight savings will depend much on the extent of use of CFR composite which in turn will depend on two things; the future approval of composite modules in the E-ferry and the commercial viability of the added cost of CFR composite module, e.g. for part of the superstructure.

If for example weight is reduced with approximately 50 ton compared to the steel superstructure. Using the found power to weight reduction ratio of 2 kW/ton. This reduces needed power, at 95 % engine load, with 100 kW from 1425 kW or around 7 %.

The savings are assumed to be of somewhat lower percentage at lower engine load as the E-ferry at 14.5 KN has a Froude number (Fn) of 0.341 placing it relatively close to the prismatic hump at Fn = 0.31.

Updated September 2015
The investment cost of any weight reduction, e.g. using more expensive materials or production methods, has to be compared to the fuel/energy savings in normal operation. In this example, energy cost is reduced with less than 7%. For an E-ferry in one year operation this would be around 200 MWh electricity to a forecasted price of less than 15,000 € per year.

In a sense, the low cost of electricity, compared to fossil fuels, makes it less attractive to invest in low weight. For an MGO driven ferry the savings would be around 30,000 € per year instead.

One could argue that the reduced weight and lower needed power would also reduce the weight of needed battery capacity with a similar percentage. For the found battery size of 3.8 MWh in the case study, a possible 4-5% battery reduction equals around 2.5 tons of battery pack or approximately 200,000 € in battery investment cost, of course heavily depending on future battery price trends.

Initial price indications shows that the cost of CFR composite modules is between 3 and 5 times higher than conventional steel ship building materials but this number is subjected to a high degree of uncertainty depending on the final composite solutions which has not developed for the E-ferry yet.

A rough rule of thumb from the producer of CFR composite elements, Tuco Marine, states that use of CFR composite materials can reduce weight of selected structures of around 60% compared to steel weights in this case. However extra insulation for fire protection measures and the final class approval most likely will add some extra weight to the composite solution, making it a little too optimistic.

In order to save some 48 tons of steel weight, 80 tons of steel should be replaced by CFR composite using this rather rough rule of thumb. The composite having a price of 3-5 times the equivalent steel weight price will result in a very long payback time, not attractive, based on the extra investment, even if both energy savings and the possible smaller battery is included in the estimate.

Most likely the CFR composite would be first commercial viable in specific parts of E-ferry where extra focus to stability issues or operational issues would be required. This could be the wheel house, the bow visor, masts etc., see illustration below;

*Figure 5.2 Most likely areas to introduce CFR composite in the E-ferry to gain on stability and reduced needed strength of hydraulics or linear electrical actuators operating the bow wisor*
It should be noted that for high speed ferries, sailing at significantly higher speeds than the E-ferry, the use of CFR composite could indeed give a much better payback time on the investment. High speed electrical ferries though are not within the scope of this feasibility study.
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