Optimizing the operation of the 100% electric E-Ferry through the use of on board charging information

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Abstract

This paper presents the concept of the E-ferry, a state-of-the-art fully electric passenger ferry, with the biggest battery capacity to date and the consequent ability to cover longer distances between charging than previously seen. As a state-of-the-art vessel, many factors of the E-ferry are yet unknown and it's likely that its operation can be optimized in a range of ways. Following a description of the overall electrical system of the E-ferry, an overview of the data types that will be collected during the E-ferry's demonstration period is provided. This data will be collected in order to monitor and demonstrate the vessel's operation, but also – and perhaps more importantly – to be able to optimize operational aspects, either of the E-ferry itself or for future iterations of the E-ferry prototype. Finally, the paper discusses a range of possible parameters of the E-ferry that can be optimized with an eye towards increasing energy-efficiency.

Keywords: *E-ferry, electric propulsion, battery packs, operation range, data collection, optimization*

1. Introduction

1.1 The Ferry market in Europe

Since 1850 when the design of the first RO-RO ferry took place in Scotland (Brambilla, Martino, 2016), the ferry industry has been progressing quickly or in a modest way depending on the financial circumstances of each era. In the late '50s, international tourism benefited from softened passport regulations which increased opportunities for holidays, and the ferry industry thrived throughout the '60s until the oil crisis which was triggered by the Yom Kippur war (1973) (Shippax, 2007, 2009). Nowadays, ferries for both passengers and cars, the so called "RO-PAX" ferries, are especially popular in Europe and beyond.

When it comes to Europe, there are three main passenger ferry markets, namely the Baltic, the North Sea and the Mediterranean, with the latter showing the highest share of passenger volumes and the Baltic showing the highest share in vehicles transported (Brambilla, Martino, 2016). As regards the routes, more than half of them are operated in the Mediterranean.

The economic recession that made its appearance early in 2008, severely affected the market, which started to recover during 2011. Today, the situation of the market actually reflects the financial state of each country and/or region (Shippax, various publications). In this respect, the operators in UK, Denmark and Ireland perform adequately, while the ones having their core business in Greece, Finland and Estonia suffer significant losses (Brambilla, Martino, 2016). On the other hand, ferry routes between neighboring countries in the North Sea and the Mediterranean are more or less stable, while they have been decreasing in the Baltic region.

With respect to fleet development, the European fleet is old and in need of newer, more energy efficient and less CO_2 emitting and polluting ferries. Mediterranean ferries are on average 22 years old (in line with the global figure), while those on the Baltic Sea and the North Sea are 16 and 14 years old, respectively (Shippax, various publications). The number of new ferries dropped from 21 in 2008 to only 10 in 2014 (Shippax, 2013).

Although South Korea, Japan and China are dominant in the shipbuilding business, the EU has been showing tremendous progress, especially when it comes to high-tech qualities (Ecorys, 2009) and sophisticated technical solutions (EC,2011, Balance, 2015). Finally and as regards the penetration of new propulsion systems, the Mediterranean ferry industry is less green that the ones in the Baltics and in the North Sea (Hoibye, 2014). All in all there are 23 LNG-fueled RO-PAX ferries in operation, of which 21 are from Norway, one from Germany and one from Denmark. One dual ferry is in operation by a Finnish operator, two hybrids in Scotland and only one all electric ferry is available in Norway (Shippax, 2013, DNV, 2014, Markinmesteren, 2015).

1.2 Major limitations and gains of electric ferries

Two of the main challenges faced by ferry services in the EU as well as around the globe are the increasing energy prices, and the demand for renewable energy-efficient sources. Recent studies by Siemens and the Maritime Battery Forum indicate that fully electric battery powered ferries provide the most optimal solution to these challenges, not to mention the significant decrease of noise pollution, especially in ports within urban and industrial areas. The introduction of fully electric ferries poses a number of new challenges, however. Current technology means that battery powered ferries are not only too expensive for ferry companies to introduce; there are also limitations in operation range.

More specifically, apart from being a novel technology, the limited take up of state-of-the-art ferries with 100% electric drive train systems is due to the fact that they suffer from major limitations in range and are thus only being built and applied for very short ferry connections. That is the case of the only ferry with electric propulsion, the Norled's aluminum catamaran "Ampere", which operates on the 30-minute route connecting Lavik and Oppedal in Norway (3 nautical miles). The ferry's batteries need to be charged after each trip, an operation that lasts 10 minutes and takes places during disembarkation (Shahan, 2015). It is therefore evident that their uptake is closely linked to the technological development of energy storage capacity.

The E-Ferry Project comes to respond to this need by developing a fully-electric battery powered ferry that can cover distances of up to 22 nautical miles. It goes beyond this limitation targeting medium range connections and aims to become the ferry with the largest battery pack ever installed on a vessel.

1.3 Goals and objectives of the E-Ferry Project

The E-Ferry Project (Prototype and full-scale demonstration of next generation 100% electrically powered ferry for passengers and vehicles), funded under the Horizon 2020 Program involves the design, building and demonstration of a fully electric powered ferry. More specifically, the E-ferry 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 vessel will be based on a newly developed, energy efficient design concept and demonstrated in full-scale operation on longer distances than previously seen for electric drive train ferries, i.e. the medium range connections Soeby-Fynshav return (2x10.7 Nm) and Soeby-Faaborg return (2x9.6 Nm) in the Danish part of the Baltic Sea, connecting the island of Aeroe (Ærø) to the mainland (See Figure 1 below). This is more than 7 times longer than the current record of 3 Nm.

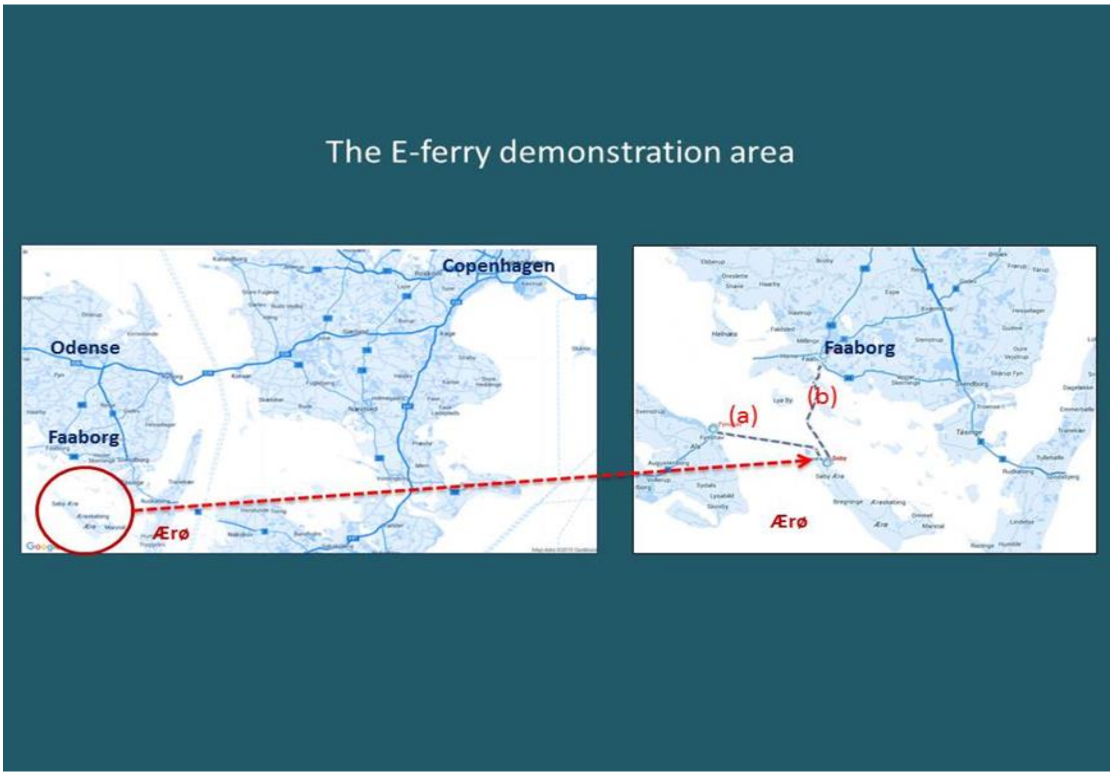

Figure 1: *The E-Ferry demonstration area*

E-ferry will have the largest battery-pack ever installed in a ferry with a record breaking high charging power capacity of up to 4.0 MW allowing for short port stays. On top of being 100% powered by electricity, the innovative novelties of the E-ferry design concept and its expected impacts addresses flaws in current state-of-the-art by demonstrating a concept based on optimized hull-shape, lightweight equipment and game-changing battery packs.

2. Development of the E-Ferry on-board electric drive train and energy storage facilities

2.1 General description

The E-Ferry vessel has been designed as a single-ended, drive-through, ro-ro passenger ferry with one continuous main deck for trailers and cars. It will operate at speeds of up to 15.5kts on two Baltic routes from the Island of Aeroe to the Danish mainland. The propulsion challenge is that each sailing is up to 10.7 nautical miles and the vessel must complete two sailings (an outbound and inbound journey), taking up to two hours in total between charges. Added to this, in the high season, the vessel will need to make up to seven sailings a day, requiring speedy recharges of no longer than 15 minutes. Based on modular units, the design developed for the E-Ferry has two battery rooms, positioned in the mid-body and aft-ship areas under deck. Each battery room contains 10 battery strings, each with a capacity of 215kWh. When fully charged, this provides the vessel with 4.3MWh of power, more than enough to complete its 22 nautical mile round-trip between charges.

The required redundancy was achieved through the designing of the system around individual battery modules. Each module comprises multiple cells connected in series or in parallel. These modules are then placed in one of the two battery rooms located on the E-Ferry, with each operating independently. With 10 banks in total, should one fail, the nine others will take over, providing the required redundancy.

The batteries are linked to two separate DC links, from where the highly efficient and lightweight 750kW Visedo PowerDRUM propulsion motors and 250kW PowerDRUM thruster motors are fed. Combined, these reduce the weight of the propulsion system by half and reduce operational costs by up to 30%. This system is expected to enable the team to dispense with a backup diesel engine, further reducing the vessel’s overall weight and positively impacting energy consumption.

In addition, because the vessel does not have a traditional engine room, it no longer requires a crew member to run it. With the battery system fully automated and operational from the bridge, the ferry is expected to be run by a crew of three (rather than the previous five), further improving operational efficiency and viability.

2.2 Installed power

The installed power of the E-ferry is totals 20 strings of battery modules; each of 215kWh. Each battery string consists of the following components:

- Battery module, which is the storage place of energy

- Battery management system (BMS), for monitoring and controlling battery usage
- Electrical protection, for battery and cabling protection
- DC/DC-converter, for loading control of battery and for creating the correct voltage

Battery System

Each battery string contains 42 battery modules, connected in series. Each module is connected to a control bus and to a BMS master. Each battery string has an independent BMS master that monitors critical cell parameters and ensures that cell voltages, temperature and state of charge remain in the safe operating area. Battery level voltage and current measurements are also part of basic functionality. The BMS of each string is connected to the DCBUS and controlled by Visedo PowerBOOST series DC/DC converters. The PowerBOOST (see Figure 2) is a liquid cooled DC/DC converter, designed especially for electric or hybrid drive trains for marine vessels and heavy duty applications. The converter has extremely compact design; 250kW converter weight is only 15kg and is designed especially for high cyclical loads. The DC/DC converters control the charging and discharging process. The main principle of usage is that all strings in a battery room are in the same state, disconnected or connected to the DCBUS. Only in case of fault, an individual string is disconnected.

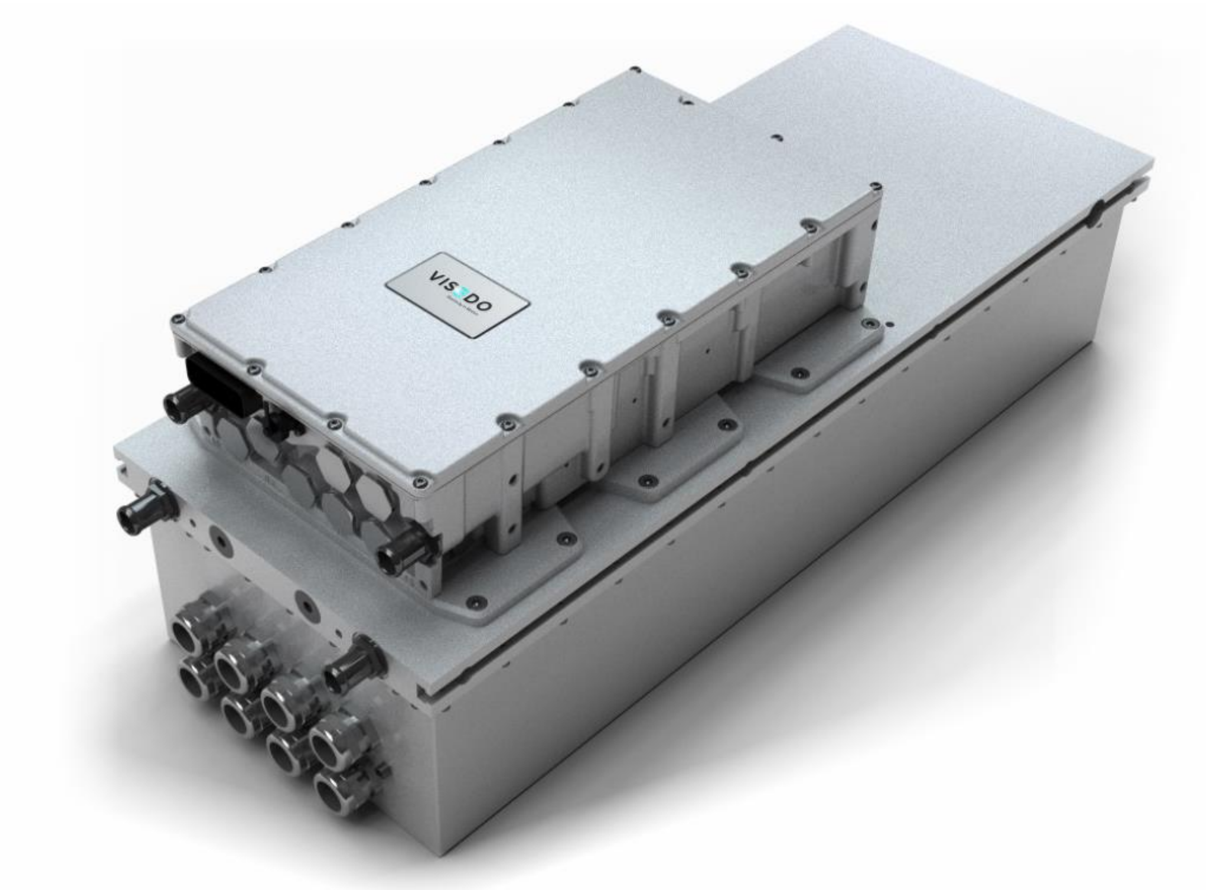

Figure 2: *Liquid cooled PowerBOOST converter with integrated inductance unit*

2.3 Consumption of energy

Since the batteries are the only main source of energy onboard, the utilization of energy is an important part of operational planning. The E-ferry's energy consumption has been defined by its operational profile, which is demanding a specific amount of power to be available for propulsion, for other consumption (e.g. lighting and heating) and for emergency procedures.

The charging process and management of the energy in the ferry is defined according to an operation profile that includes six round trips per day. The "hardest" operation profile (Friday and Saturday in the high season time) includes 7 trips during the day. Each return trip is 1h and 55min long. During the day there are six 20min charging breaks, one longer 40min lunch break and one 7,5hour night time break, with the battery being charged during each break.

The charging and discharging processes need to be analyzed on equipment level in order to be able to understand the total power consumption and losses of power conversion. Losses caused by AC/DC converter, transfer, distribution, inverter and electrical motor are also taken into account.

Energy balance for the battery shows that it has over 1.5MWh of reserve energy available throughout the day, in the beginning of the battery life. At the end of battery life the capacity decreases which must to be taken into account on planning sailing profile and charging times for later years of battery life.

Finally, the hotel consumption considers the electrical consumption outside the propulsion utilization. In this respect the battery driven ferry is a quite simple design, since plenty of the engine room arrangements, systems and auxiliary energy consumption is not needed in this installation. The main engine room consumption is related to the cooling circuits of propulsion and power plant components, as well as some air conditioning.

2.4 Management of energy

The Energy Management System, traditionally called the Power Management System (PMS), is required for automatic operation of practicalities. The human-machine-interface (HMI) of the PMS is located on the bridge and has been designed specifically for the project.

Based on this, the E-ferry PMS is used for:

- Monitoring and practical information of the power plant through HMI;
- Informing and guiding the operator in regards to energy capacity available for operation;
- Allowing the user to utilize automatic mode functions
    - Charging modes
    - Sailing mode
    - Harbor mode
- Providing accurate power plant data to vessel automation system/office monitoring link.

<u>*Charging mode*</u>

During the day-time harbor visits on Aeroe, the vessel will charge using the Fast Charging Mode. This is required in order to keep the charging level at a safe level throughout the day. It will be achieved using the shore charging capacity at its rating level, providing maximum energy flow from shore to ship and will be activated by the captain (or bridge personnel) at the approach of the vessel.

During the long night-time break, batteries are charged slowly, using the Night Charging Mode. The vessel is required to stay in the charging position throughout the night, in order to provide the maximum charging level of batteries in the morning. This is activated by the captain (or bridge personnel) at the moment of docking the vessel.

Sailing Mode

While 'Sailing mode' is activated, the vessel prepares for the disconnection of the shore line and for the use of the propulsion. The Captain activates the sailing mode at bridge. In the propulsion control system HMI the energy capacity of the power plant is indicated constantly.

Harbor (manual) mode

While Harbor mode is activated, the vessel remains on the minimum consumption level. During the vessel's stay in operation, it remains mainly in the charging modes in Aeroe-end and in sailing mode. Harbor mode is mainly designed for the other end harbor and for longer harbor stays outside the normal operation. In Harbor mode, manual operation of all onboard consumers is possible.

3. Collection of on-board data

All data pertaining to the battery system and the electrical propulsion system, such as for instance battery condition (state of health and state of charge) and performance, power loads in different operational modes and conditions, as well as individual electrical components performance will be collected onboard the E-ferry as part of its daily operation. Much of this data information is transferred directly to the HMI at the bridge, so that the daily operator (Captain) can monitor the energy capacity available for operation and determine what mode to enter based on this. In order to further monitor, optimize and demonstrate the operation of the E-ferry, a large set of operational and environmental data will in addition be collected onboard the E-ferry during its demonstration phase.

3.1 Types of data that will be collected on board

The types of data that will be collected onboard the E-ferry can be separated into four main categories; technical systems and battery data, technical vessel data, navigational data and meteorological data.

Technical systems and battery data:

- Cell voltage
- Cell temperature
- State of charge
- State of health
- Emergency power
- Load request
- Energy flow

Technical vessel data:

- Power measurement for each power producer;
- Main engine RPM for each shaft;
- Main engine shaft power;
- Speed through water;
- Speed over water level;
- Power consumption for each main consumer;
- Angle of rudder;
- Fin stabilizer status;
- Power produced by shaft;
- Rate of turn;
- Main switchboard powers;
- Chiller powers

Navigational data

- RPM propeller for each shaft;
- Propeller shaft power;
- Speed through water;
- Speed over ground;
- Wind speed;
- Wind direction;
- Water depth at keel;
- Draft of vessel;
- GPS position and course;

Meteorological data

- Sea water temperature
- Outside air temperature
- Outside humidity
- Wind speed
- Wind direction
- Sea current speed
- Sea current direction
- Water depth below keel

3.2 Methodology

The data will be collected through the E-ferry's Integrated Automation and Information Management System(s) (IAS), delivered by Valmet. The IAS is designed as a Supervisory Control And Data Acquisition (SCADA) system with remote control of the various utilities, so that it can be be supplied by information both from the PMS, all control units (consumption, propulsion and bow thruster) and from standard navigational and meteorological ship systems. The IAS will then collect the data into a common signal list, from where relevant comparisons and analysis can be performed, depending on the intended purpose of the data collection. The signal list will be transferred to shore once a day, during the night, when the vessel is 'resting' and in Night Charging Mode. Transfer and data storage will be done with a cloud based DNA Process information system, and through Virtual Private Network (VPN) technology that ensures secure and encrypted communication to shore.

3.3 Potential dangers

The main danger involved in the data collection is that data can be lost and that the transfer could be hacked by outsiders in an attempt to take over control of the vessel. By automatic transfer of data to safely stored hard discs on shore every day, the amount of data that could feasible be lost is minimized. By transferring data only from vessel to shore through the VPN and in a system where commands that go from shore to vessel is not possible, the system should ensure that even if hacked, access to the operational aspects of the vessel would not be gained.

3.4 Purposes served by the collected data

The purposes of the collected data are to provide an overall picture of all aspects of the E-ferry's operation, so as to be able to both monitor and demonstrate the E-ferry's operation.

Monitoring:

For daily monitoring of the E-ferry's operation, it is mainly the technical data that will be considered. This data will allow the operator as well as the technology suppliers to monitor the overall performance and health of the electric system, including the battery strings and individual modules of these strings. Such daily monitoring will allow both operator and technology supplier to determine whether the systems are performing according to expectations and specification and make any relevant adjustments, if needed. Daily monitoring will also allow for identifying any potential faults or defects in the system, so that individual component can be replaced as and when necessary. It will also allow the technology suppliers to control that the operator is operating, maintaining and servicing the systems in the manner instructed.

Demonstrating:

For the purpose of demonstrating the E-ferry's potential, technical, navigational and meteorological data will be combined. By bringing together all this data, it will be possible to provide a full profile of the energy efficiency of the E-ferry and to thus identify and demonstrate the most optimal conditions under which the E-ferry can be operated, in terms of for instance route and schedule planning, mode(s) of operation and meteorological conditions. By identifying also the conditions under which the E-ferry is less optimal, in terms of energy efficiency, it will be possible to present a realistic business case from which future implementations of the E-ferry prototype in other areas of Europe could be determined. Finally, a full-scale demonstration of the E-ferry, with all the relevant data considered, will make it possible to determine how future E-ferries can be scaled for other routes and operational conditions, e.g. in terms of the overall size and proportions of the vessel itself, as well as with respect to the capacity of the battery pack and the propulsion system

4. Optimization of operation through the use of the on-board data collected

As the E-ferry is a state-of-the-art vessel, with the highest battery capacity seen to date and with a scale of operation that is hitherto fore unseen, data collection is also needed for determining and subsequently optimizing the E-ferry's operation. In this respect, the E-ferry will constitute a floating laboratory, in which daily data information is collected and analyzed. The results of the analysis can then be fed back into the E-ferry as adjustments of various parameters, after which these adjustments can be further analyzed and recalibrated to optimize the operation of the E-ferry.

4.1 Necessary data for the understanding of operation

All data described above are necessary for understanding the operation of the E-ferry. While each set of data provides important information about the E-ferry's systems and the conditions under which it is operated, it is only by combining the different datasets that it will be possible to determine which parameters may have an impact on the overall operation and to what effect. Questions that can be asked by combining the different data sets are, for instance:

- What are the biggest energy-consumers onboard the E-ferry?
- How big is the energy-loss from shore to propulsion for the E-ferry?
- Where is the biggest loss of energy located between shore and propulsion?
- To what degree do meteorological conditions impact the energy-consumption of the E-ferry?
- Which meteorological conditions have the biggest impact on the energy-consumption of the E-ferry?
- How much and at what point does the state-of-health of the battery pack impact the operational range of the E-ferry?
- To what degree do different operational modes (docking, cruising etc.) influence the overall energy-consumption of the E-ferry?
- Under what conditions is it more energy-efficient to use which components of the propulsion system?
- At what speed and under what conditions is the E-ferry at its most energy-efficient level?

4.2 Optimization of the E-ferry operation

Based on questions such as those listed above and the answers that will be provided through the detailed data collection and combining of the different data sets, the operation of the E-ferry can be optimized by adjusting and re-calibrating certain parameters – and possibly even replacing certain components. Any such adjustment will of course have to be based on a detailed cost-benefit analysis. The replacement of certain consumers with alternative consumers that are more energy-efficient may, for instance, prove too costly when compared to the amount of energy that can be salvaged over the E-ferry's expected life-time. Likewise, it may be the case that reducing the speed of the vessel or the number of trips taken on a daily basis could save a significant amount of energy, but not be feasible from the point of view of the operator. Aside from these speculations, however, the combining of the various data sets described above could lead to the discovery of a large range of adjustments that could serve to optimize the operation, either of the E-ferry itself or of future otherwise similarly designed fully electric vessels:

By investigating the different consumers onboard the E-ferry, it will be possible to optimize the overall consumption, as well as each individual consumer: main consumers such as propulsion motors and thrusters could be scaled down - if operationally possible – or the optimal RPM in terms of energy consumption could be identified and the motors could be calibrated to function mainly at that RPM. Any hotel consumers that are identified as large consumers could possibly be replaced by more energy-efficient alternatives.

By investigating the energy-loss from shore to propulsion, and in particular by identifying where the biggest loss occur, new dimensioning of the overall electric system could be proposed and possibly implemented in future iterations of the E-ferry. For instance, it may be revealed that the biggest loss occurs between the transformer house and the charger, this loss could be decreased by minimizing the distance between the two as much as possible, as any loss in this location is expected to be directly tied to the length of cables. Other major losses could be identified as being located in the converters; if this is the case then further development of the converters would be required.

By combining the data pertaining to energy-consumption in particular for the propulsion system on the one hand, with the meteorological data and the technical vessel data on the other hand, it will be possible to determine how the different sailing conditions may or may not influence the energy-consumption of the E-ferry. The data can show, for instance, whether the energy-efficiency of the E-ferry decreases in difficult sailing conditions, i.e. in stormy weather, at strong currents or depending on the level of water below the keel, for instance at low or high tide. The possibilities for optimization of the E-ferry's operation might not be very big in such cases, as the operator has no control over weather conditions and because it would probably not be operationally feasible to organize the E-ferry's schedule around meteorological conditions. The more specific sailing-route of the E-ferry could however be calibrated towards optimizing the daily operation with respect to the meteorological conditions, so that the Captain and crew could for instance be instructed to plot a certain course depending on for instance the strength of the wind, wind direction, or current and/or increase or decrease the speed of the vessel depending on the depth of the water level below the keel. Finally, such data could be implemented in the consideration of subsequent designs of similar vessels and could be used to identify the most optimal routes in which such vessels can operate in the future.

In the same way, optimization of the E-ferry could be based on comparing data that pertain to the different operational modes of the E-ferry with those data that concern the overall energy-consumption and efficiency. The E-ferry will be operating at different modes, e.g. entering and leaving the harbor, docking and basic cruising between harbors; during these different modes of operation, the E-ferry will be operating at different speeds and directions and different components of the propulsion system will be used to different degrees. By investigating the correlation between these different modes and the level of energy-efficiency for each of the modes, it will be possible to identify whether there are modes in which the E-ferry is less energy-efficient and whether anything can be done to optimize these modes, either through operational means such as reducing the use of the less energy-efficient modes or through technical means such as calibrating the different components of the propulsion system.

5. Conclusions

Although the three major ferry markets in Europe (The Baltic, the North Sea and the Mediterranean) have been severely affected by the recession, they started to show signs of recovery earlier than other sectors, around 2011. In general, it is safe to say that the ferry industry is susceptible to change based on positive or negative variations in transport demand (Brambilla, Martino, 2016).

Although the European Union has spent more than 306€ million to the maritime sector through various funding projects (TEN-T, CEF, MoS, etc), it is not possible to define what part of these funds has been attributed to the ferry industry (EC, 2009d). Moreover and despite the goals set by the EC for reducing the increasing European CO_2 emissions from waterborne transportation (EEA, 2015) the actual number of ferries delivered with new propulsion systems and compliant with environmental rules is significantly below initial predictions (Brambilla, Martino, 2016; Lloyds Register, 2012; DNV, 2013). The use of new propulsion systems is actually very low, while when it comes to electric ferries there is currently only one in operation.

This is partly due to the limitations that electric ferries face, related to low range of operation and high cost of batteries. The E-Ferry Project comes to respond to this need by developing a fully-electric battery powered ferry for longer distances than previously seen. More specifically it is expected to complete two sailings of 10,7 nms each prior to being charged. This goes beyond the above mentioned limitations, targeting medium range connections and aiming to become the ferry with the largest battery pack ever installed on a vessel. To add up to the ferry's advantages, it should be noted that due to the lack of an engine room, it can be run by a crew of three improving thus operational efficiency.

In order to further optimize the ferry's operation, it is necessary to efficiently plan the use of onboard energy. One of the basic functions of the E-ferry is therefore considered the battery's Human Machine Interface (HMI), which allows the collection and assessment of the necessary information ie. technical system and battery data, technical vessel data, navigational data and meteorological data. Based on this knowledge the necessary each time actions can be planned and undertaken in order to optimize the overall operation of the ferry and ensure the highest possible environmental gains. The optimization of the ferry's operation will be best achieved by combining the different types of data collected. This way, the E-Ferry will actually act as a floating laboratory, allowing the identification of the most optimal scheme of operation, which can also be adjusted to various circumstances in different markets. These adjustments will of course have to be based on detailed cost-benefits analysis.

Some of the adjustments that may be made in order to ensure the optimization of the ferry's performance based on the combination of the different data sets include the following:

- Optimization of the overall energy consumption by identifying major on-board energy consumers.
- New, optimized dimensioning of the electric system of future iterations of the E-ferry based on the investigation of energy loss from shore to propulsion.
- Identification of the effects of weather conditions (meteorological data) on the vessel's energy consumption, with the goal to optimize daily operation according to occurring weather conditions;

- Mapping of different operational modes to energy consumption occurring each time, in order to identify the most optimal and energy efficient in each case operational mode.

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