URBAN FERRIES: COMBINING TECHNOLOGIES AND OPERATIONAL PROFILES

D de Koningh, Damen Shipyards Gorinchem, NL
A Vrijdag and **H J Bosman,** Delft University of Technology, NL

SUMMARY

For conventional propulsion systems, numerous design methods exist to help with an efficient concept design process. However, once energy storage devices are considered in the system configurations, the existing methods have their shortcomings. It is the experience of Damen that good understanding of the link between energy storage device (ESD) characteristics, charge and discharge strategy and the operational profile (route plus timetable) is crucial. To the knowledge of Damen, no proven method exists that helps to reach a sensible system solution including ESDs, in an early stage of the design process, nor one to optimize such a system for maximum efficiency.
Within the EU JOULES project, Damen is looking into possibilities for future design of urban ferries. This paper describes the effort to find a holistic approach to the integration and optimization challenge Damen faces as a shipbuilder. As will be shown, it is a complex puzzle involving domain (ship) knowledge, component knowledge (suppliers), integration knowledge and a good view of the operational profile in consultation with the end-user. This paper describes how time domain simulation is used as a powerful tool to support the integration of components and how it supports the optimization of such a system. The paper mainly focuses on the process of selecting and integrating the appropriate energy storage device given a specific operational profile. Furthermore this paper gives insight in the more political process of challenging the established design processes within Damen Shipyards and judge its applicability in future ship design where energy storage other than fossil fuels play a big role.

1. INTRODUCTION

In shipbuilding industry the request for ship designs containing alternative energy storage devices (ESD) to reduce emissions becomes more and more noticeable. Recent alternative ESD design developments within Damen Shipyards in combination with work done for the JOULES (Joined Operation for Ultra Low Emission Shipping) project provided the basis of this paper [1]. First an alternative ESD test case is discussed, subsequently the influence on the design process when designing alternative ESD is discussed. The vessel as used in the test case is the Damen Fast Ferry (DFF) 3007, a 30 meter aluminium catamaran passenger ferry capable of top speeds of around 40 km/h. The vessel operates between the Dutch cities of Rotterdam and Dordrecht; a densely populated area making emission reduction even more relevant.

2. BENCHMARK SHIP

Figure 1 shows a Damen Waterbus in Rotterdam. This fast sailing aluminium catamaran is especially designed for transport in Urban Areas. The vessel is approximately 30 meters in length and 7 meters in width. It is suited for transport of up to 130 people and can carry 40 bicycles on the aft deck. As shown in figure 2 it is propelled by two fixed pitch propellers which are driven by two high speed diesel engines of 366 kW each, driving the ship up to 40 km/h. The small electric hotel load is generated by a separate generator set. The two bow thrusters are driven hydraulically by gearbox mounted hydraulic PTOs.

The route between the cities of Rotterdam and Dordrecht is visualized in figure 3, which shows the 7 stops along the route plus the observed speed profile between the stops. The speed profile of the ship was obtained by means of multiple GPS measurements. These measurements plus the observed manoeuvring actions of the captain gave a good idea on how the ship was used.

Four different runs are shown in figure 4, which shows various interesting aspects: first of all it shows that in some occasions the captain does not stop if there are no passengers that want to (dis)embark. Secondly the effect

Figure 1: A Damen Waterbus in Rotterdam

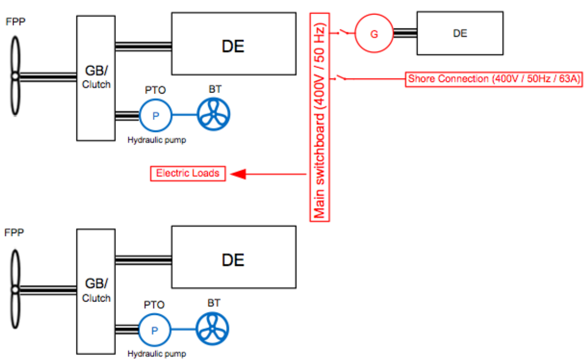

Figure 2: System diagram of the benchmark vessel

of the current is clearly visible in the top speed. In this case the speed difference between the two directions is around 6 km/h, which means that a current of around 3 km/h was present. Furthermore one can see that roughly 3 different speeds are used: 0 km/h, 20 km/h and 40 km/h. The intermediate speed of 20 km/h is used to prevent unnecessary annoyance to moored vessels.

The operating profile of this urban ferry (and of urban ferries in general) is characterized by relatively short distances between hubs. This raised the question whether it would be possible (in the foreseeable future) to use alternative (electric) energy storage devices on an urban ferry, resulting in zero local emissions. The expectancy from the beginning was that this would conflict with the requirement of a low weight, high speed ship, as alternative energy storage devices are considered large and heavy. Despite initial hesitation it was decided to investigate an alternative power and propulsion concept.

In the following paragraph, characteristics of various (available and experimental) ESDs are discussed including values of specific power and energy density. Based on the characteristics a potentially suitable (or at least a most promising) ESD will be selected.

3. ALTERNATIVE ENERGY STORAGE

The conventional way of storing energy is by use of chemical energy storage in the form of fuel. Practically 99 % of the vessels recently produced by Damen use fossil fuels as only energy storage medium, mainly for their beneficial energy density, price and internationally well-organized infrastructure. Some exceptions are the recently delivered hybrid tugs (diesel direct with batteries) [2], hybrid canal patrol boat and wind driven vessels (clippers). The search for more sustainable power

Figure 3: Route Rotterdam to Dordrecht including measured speed profile for each leg between the stops

plants boosts the search for alternative energy storage means. Alternatives can be found in: mechanical (any form of kinetic or potential energy storage), electrical (electrochemical and magnetic), thermal (store energy as heat or cold) and renewable and CO_2 neutral biological (glycogen, fat etc.) energy storage. For each of these energy storage means, devices exist that are, to some extent, feasible applicable in the maritime industry.

3.1 ESD COMPARISON

To judge the ESD applicability and feasibility in a specific power plant in the maritime transport sector, a quantitative and qualitative comparison has to be made between the different energy storage alternatives. The most important criteria according to which the ESD can be compared are:

- energy and power density (energy or power to power plant weight ratio),
- efficiency,
- ESD cycle life,

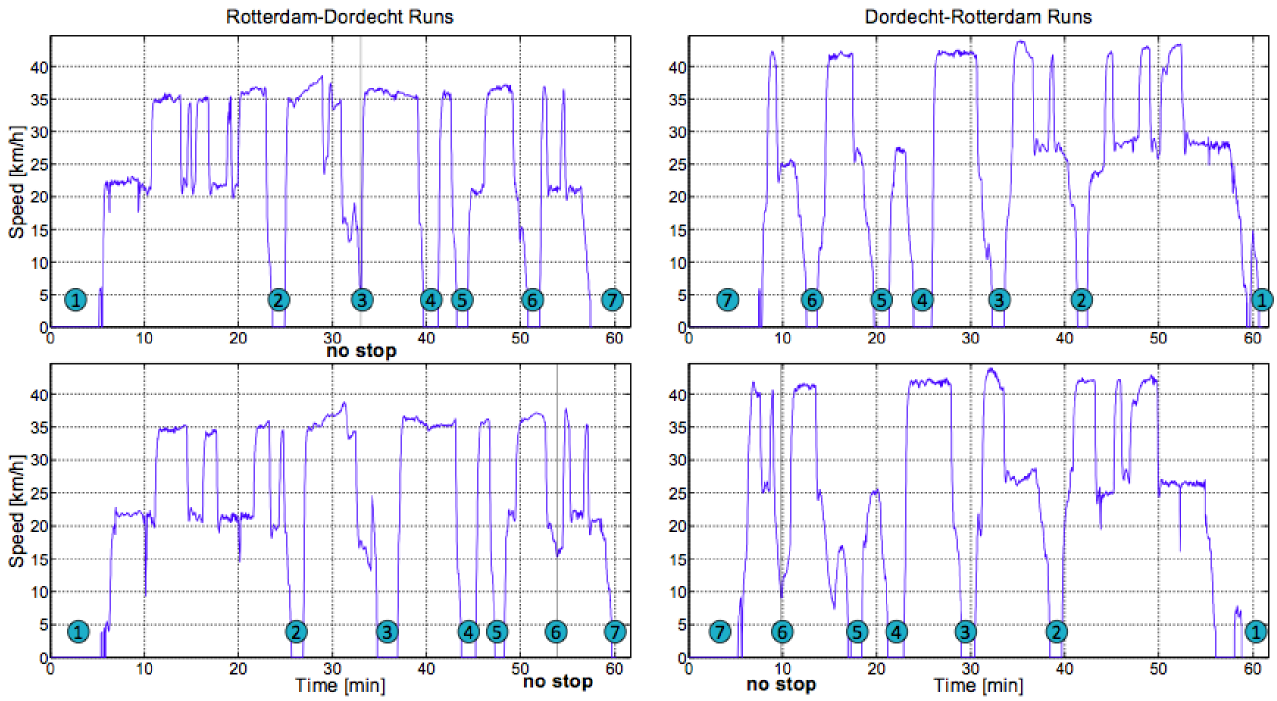

Figure 4: Four different measured speed profiles

- environmental footprint,
- ESD behaviour
- costs (CAPEX / OPEX),
- safety

Above subjects are explained more in detail below for the urban ferry case specifically.

3.1 (a) Energy and power density

The Ragone plot [3] offers a comparison of energy storage devices and their application in power plants in terms of energy- (vertical axis) and power (horizontal axis) density. The graph is useful for a preliminary selection of ESDs, but should not be used for a detailed power and energy density analysis. Most of the ESD data is taken from, often non-validated, manufacturer's datasheets and it consists of ESDs that are still under constant development. Furthermore, various theories exist on how to determine the 'border' of the system to determine weight or volume. For these reasons many forms of the Ragone plot exist and every system designer should at least validate the content or create their own updated version. Figure 5 shows the version as used by Damen for the urban ferry project. The benchmark vessel (diesel direct propulsion with fuel as energy storage medium) is plotted in this graph too. To calculate the density, the weight of the total propulsion system is taken into account including secondary systems and fuel storage tanks. The dotted lines indicate the movement in the Ragone plot when the fuel capacity changes; e.g. increasing the diesel fuel tank capacity increases the energy density since without adding much mass besides the fuel itself, the range increases. At the same time the power density drops, since with the same installed power the weight of the total system (fuel included) increases.

In this study a full ESD replacement is taken into account which means no 'hybrid' solutions that combine multiple ESD are considered. Therefore, the required power and energy density can be drawn in the Ragone plot directly.

3.1 (b) Efficiency

Optimisation is a core objective for a ship designer and not limited to sustainable alternative ESD design. In general efficiency is mostly referred to by clients in terms of fuel consumption, which is obviously only applicable when using fuel as energy storage device. Every alternative ESD has its own measure of efficiency influenced by charge, discharge and storage efficiency. These properties are captured in a round trip efficiency which compares energy input with useful energy output.

3.1 (c) ESD cycle life

When considering a conventional propulsion train with diesel engines, the influence of different operation modes on the lifetime of the propulsion plant is well known. Engine manufacturers have specific rules regarding the time an engine can operate in a specific speed and load condition. Based on the use of the engine, service intervals are prescribed that guarantee the lifetime of the engine when properly executed. Since the large scale implementation of alternative ESD is a recent trend, limited reliable long term statistical data on the lifetime of these devices is available, e.g. for batteries, lifetime is highly dependent on the charge and discharge rate, number of load cycles and cell temperatures. Alternative ESDs have, depending on the use with respect to charge and discharge strategy, usually a lifetime of 2-6 years which is much less than conventional propulsion

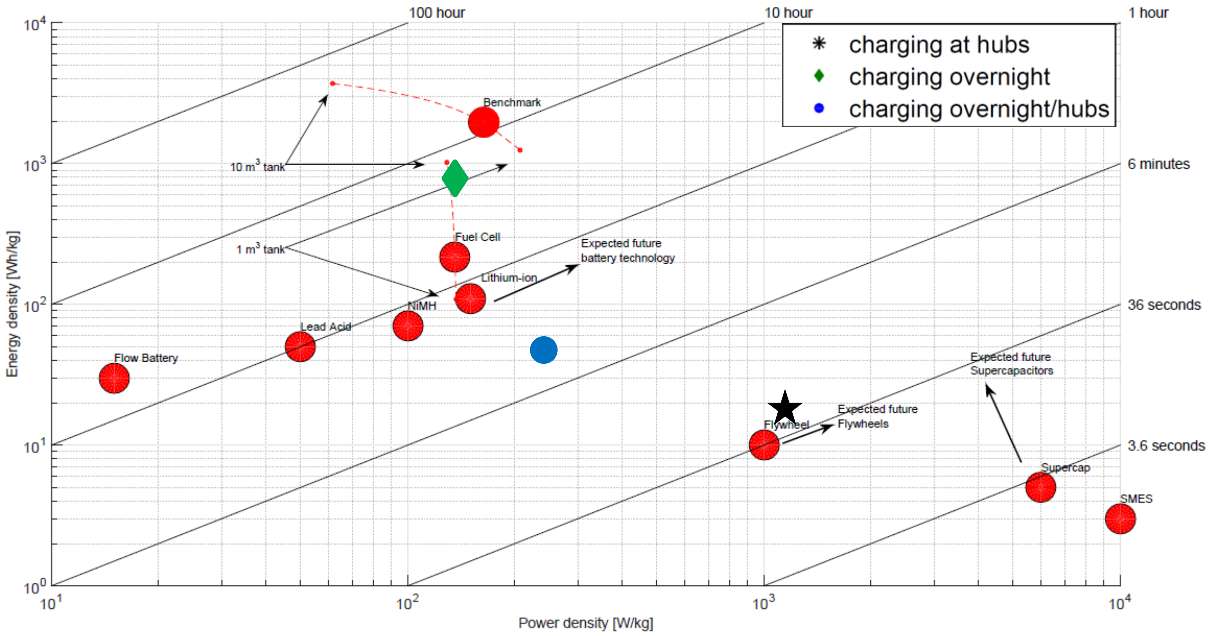

Figure 5: Ragone plot showing different ESD operating area's and energy demands

systems. The casco and outfitting lifetime will outrun most ESDs considerably therefore making it necessary to take regular replacement into account and include ESD cycle life in the total assessment.

3.1 (d) Environmental footprint

When alternative ESDs are applied, it is mainly to reduce emissions and contribute to a more sustainable design. The challenge is, especially when talking about sustainability, to set the boundaries of the system and impact region that is being considered. For the urban ferry case it is beneficial to lose all local emissions since it operates in highly congested urban areas. The power that is needed to charge the batteries or to create H_2 for the fuel cells can then be generated by renewable energy sources on large scale on a centralized location. A life cycle assessment with an indication of the cradle to cradle sustainability of ESD production and decommissioning phase completes the analysis.

3.1 (e) ESD behaviour

It has to be determined if the ESD can cope with the required load demands of the propulsion system. E.g. batteries react quickly to load variations, but a fuel cell can only operate at relatively constant loads. The operational profile of the urban ferry shows many accelerations and decelerations which requires an additional ESD (flywheel, capacitors or batteries) to be used for peak shaving when a fuel cell is considered.

3.1 (f) Costs (CAPEX /OPEX)

In the end, costs determine mainly the outcome and feasibility of the design, especially when considering 'fancy' alternative ESDs. Initial investment costs are mainly driven by the complexity of the ESD itself. The operational costs are mainly driven by service costs and lifetime of the ESD. In case a highly promising, but premature alternative ESD is applied, in can be expected that the design, implementation and commissioning will result in very high costs.

3.1 (g) Safety

With some ESDs hazardous equipment or fuels are involved. Especially in case of the urban ferry, which operates in communal environments, safety plays an important role. Complying with safety standards, rules and regulations may take a lot of extra effort when for example applying fuel cells with accompanying explosive H_2 stored in tanks.

3.2 ESD PRE-SELECTION

At this very early stage in the system design process many questions arise regarding the ESDs and their characteristics. Some examples are given here to demonstrate the complexity of this seemingly relative straightforward system design task: Which ESD should be chosen? Should we charge the ESD at every stop or perhaps charge only once per day? What if we make the stops a bit longer such that we can charge more energy? What is the effect of maximum shore power that can be supplied? What would be the effect of sailing at a lower speed? Would it be beneficial to add an extra stop between stops 1 and 2? What is the effect of all these options on the lifetime of the ESD? Under which conditions would the ESD concept be economically viable? Would it be wise to lengthen the vessel at equal draft in order to carry more ESDs, at the cost of only slightly increased ship resistance?

These questions are just a few examples that demonstrate the huge amount of options that a (system) designer has in the early system design phase of an ESD powered ferry. The fact that many aspects are strongly interconnected complicates the task even more. It is the experience of the authors that traditional design processes for normal ships and their power and propulsion systems, as used for many years, suddenly don't give a clear indication in which to proceed. This led the authors to the idea that a time domain simulation tool could be helpful in making the various important choices that are to be made at an early stage.

To decrease the required modelling effort it was decided to make the selection of the type of ESD based on simplified calculations since it required too much effort to model all types of ESD in a time domain simulation model. The remainder of this paragraph deals with this ESD pre-selection process. Subsequently the simulation model itself and some preliminary results are presented.

The mentioned ESD pre-selection process involves two steps:

- Derive the amount of power and energy that the ship 'requires' by combining observed operating profile and the known vessel characteristics for power and propulsion.
- Investigate how 'much' kg of ESD the ship can carry by analysing the weight balance of the ship, taking into account removal of the fuel, the diesel engines and installing electric motors, frequency drives and switchboards. The chosen starting point was that the conceptual ship with ESD configuration should not be heavier than the original ship.

The idea is that the combination of the 'required power and energy' and the 'maximum allowable weight and volume of the ESD' would lead to a first idea of required power and energy density. This would only be a very crude first idea but it would help to make an initial rational selection out of the many available ESD types.

The derivation of the required energy and power that the ship requires along the route is based on a simplified ship energy grid model consisting of easily available data on the ship resistance curve, open water propeller data, propeller-hull interaction coefficients, a parametric gearbox efficiency curve, a parametric specific fuel consumption curve of the propulsion engines and an assumed electric hotel load. This simple model is not discussed here in detail since it is only used to get a first feeling for the amount of energy and power required for this route. The model output is validated with available full-scale measured data from an earlier measurement campaign as shown in figures 6 and 7. The location of the dots in relation to the line confirms that the simple model is sufficiently accurate for first estimates.

Based on this validated simple model and a schematic operating profile as shown in figure 8 (derived from figure 4), the required energy and power along the route is calculated and visualised in figure 9. There it is shown that the maximum required shaft power is just over 600 kW, and the total required energy for a total 1 hour trip from Rotterdam to Dordrecht is around 270 kWh including the small auxiliary load. A more detailed overview of the required energy per leg (figure 3) is given in table 1 for reference.

As explained before, the second step in the ESD pre-selection is to calculate the amount of ESD weight (volume is not discussed in this paper) that can maximally be carried by the ship, taking into account the

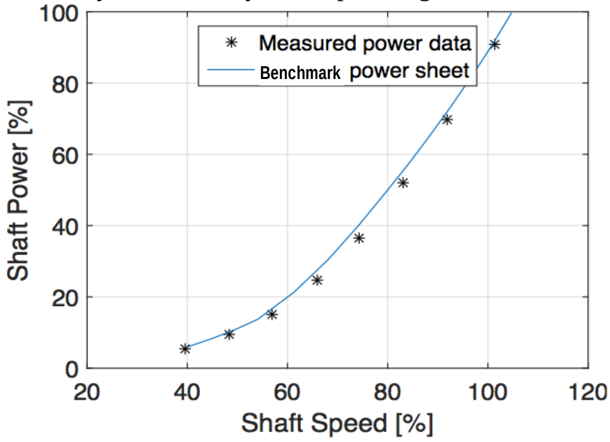

Figure 6: Validation of shaft power vs. shaft speed

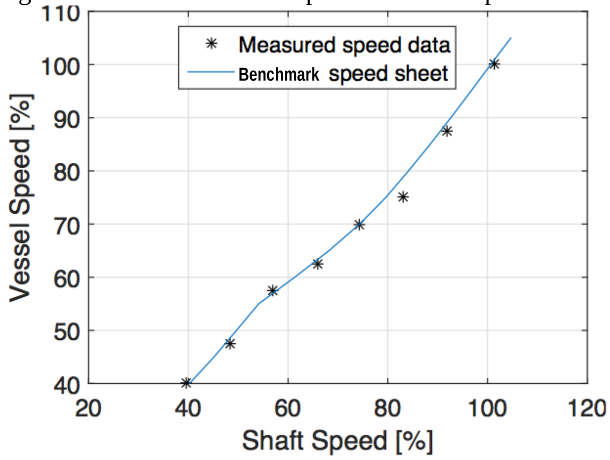

Figure 7: Validation of ship speed vs. shaft speed

removal of fuel (plus tanks), diesel propulsion, and other components including electric motors and

Table 1: Overview of required energy along the route

Leg	Energy demand [kWh]
1-2	94
2-3	51
3-4	51
4-5	8
5-6	42
6-7	23
Total 1-7	**269**

frequency drives. This 'weight for weight exchange' calculation is based on an assumed future 'full ESD' configuration as shown in figure 10. Note that this configuration includes gearboxes, while it might seem logical to install electric motors that can operate at the relatively low required propeller rpm in order to save gearbox weight. This option has been considered but until now the combination of a high speed electric motor and the gearboxes is found to have the lowest weight. This might change in the future. Further note that the bow thrusters are removed: this is a conscious choice since these thrusters are seldom used nowadays.

Only a simplified weight calculation is given in this paper. The amount of weight installed in the current

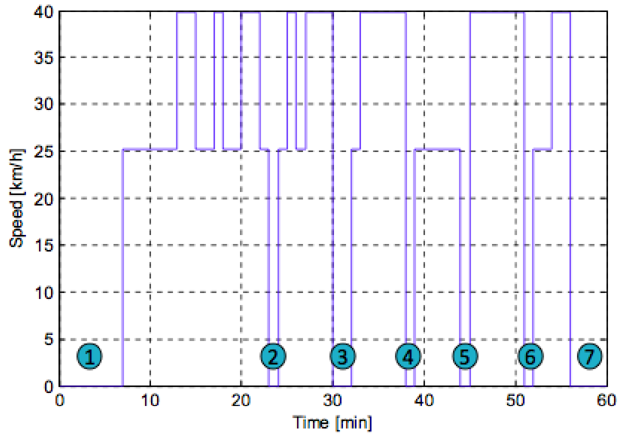

Figure 8: Averaged reference speed profile

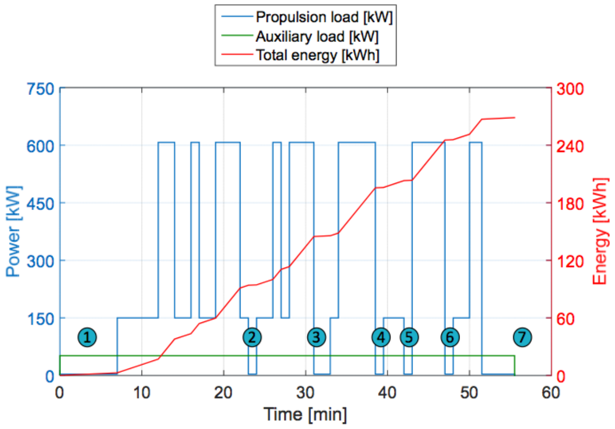

Figure 9: Energy and power demand, based on the averaged reference speed profile

(traditional) configuration that can be removed is shown in table 2, and amounts to a total of almost 8500 kg.

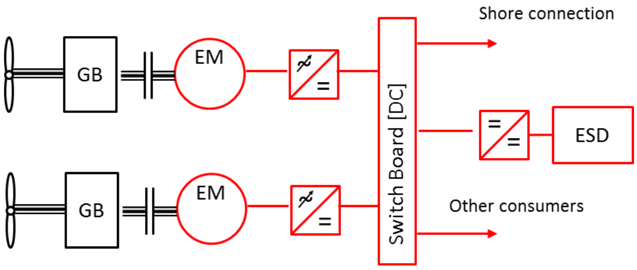

Figure 10: Full ESD configuration. In the simulation model batteries are used as ESD.

Table 2: Weight that can be removed from the benchmark vessel

Propulsion (main engines, gearboxes etc.)	*4700 kg*
Electric system	*2000 kg*
Fuel and lubrication oil	*1720 kg*
Total	**8420 kg**

Table 3: Weight required for full ESD configuration (excluding ESD itself)

Gearboxes	*440 kg*
Frequency drives	*825 kg*
Electric motors	*558 kg*
Switchboard and cabling	*788 kg*
Other supporting systems	*500 kg*
Total	**3110 kg**

The assumed weight that is required for all equipment in the full ESD concept, excluding the ESD itself, is listed in table 3.

It should be noted here that the weight estimation of the above components is based on a weight database based on available manufacturer data, in some cases extrapolated to the required component power. From the two tables shown above it can be calculated that the weight of ESD that can be installed (without superseding the original weight) is slightly over 5000 kg.

At this moment both the 'available weight for ESD' and the 'required energy and power' are available such that the key figures for ESD selection can be calculated; the required specific power density W/kg and the required specific energy density Wh/kg can be calculated. However, the shore charging strategy strongly influences the required specific energy density and therewith potentially the selection of the ESD type. To clarify this three examples are given here:

- One option is to assume that the ESD will be charged at every stop and thus has to contain only little energy.
- Another option that is worth testing is to see whether an ESD exists that can carry enough energy to sail all day long without intermediate charging.
- Combinations of charging overnight and at stops are also possible.

Again it becomes clear that the pre-selection of ESD type is so closely interlinked with the charging strategy and the ship operating profile that one could ask whether the idea of ESD pre-selection via simplified calculations is a good idea at all. In the end calculations of 'required specific energy and power density' were made for all 3 abovementioned charging strategies and were plotted in the earlier presented Ragone plot to compare the requirement with the available ESD types. The result is shown in Figure 5 that can be found a few pages back. The three shown charging strategies are subsequently briefly discussed.

3.2 (a) Charging at every stop

As found earlier, the required energy for one run is 287 kWh (energy from table 1 plus additional charge and discharge losses). The maximum energy needed for one leg is found to be 101 kWh (leg 1-2 which is the longest). The maximum power during one run, which is similar for every leg, is roughly 660 kW when combining propulsion and auxiliary load (see figure 9). To calculate the specific power and energy densities the aforementioned power and energy are divided by the available weight for the ESD, which is 5310 kg.

Charging 101 kWh in a short stop of 1 minute results in roughly 6 MW of required charging power, which is assumed unrealistically high. Although the flywheel in the Ragone plot comes relatively close to the ESD requirement when charging at hubs, the required charging powers are assumed too large for practical use. Therefore the charging at hubs is not further considered in this paper. This does not say that a flywheel could not be a good option for ferries with other operational profiles, this should however be considered on a case-by-case basis.

3.2 (b) Overnight charging only

According to the timetable the vessel sails 15 hours a day in summertime. The total energy needed for the 15 hours of sailing is 4305 kWh, the maximum power is independent of time and therefore still 660 kW. If the available ESD weight of 5310 kg is used, the specific power and energy density become respectively 124 W/kg and 811 Wh/kg. The numbers determine the location of the green dot in figure 5 (a 9 hour overnight charge is available to charge all the energy that is needed). Although the power density is not that high, the energy density is. In the Ragone plot the requirement is closest to the benchmark configuration. The fuel cell is also in range but is not considered due to practical problems and local H_2 refuelling hazards. The requirement of roughly 811 Wh/kg for the ESD is assumed unrealistic for current and future ESDs and therefore the ‘charging overnight strategy’ is not further considered.

3.2 (c) Combination charging overnight and at hubs

The third charging strategy option is to fully charge the battery overnight plus intermediate charge during the sailing route, when the vessel is moored at the different hubs. This option not only brings the maximum required stored energy down, but also brings the charging powers down. The total energy needed on-board has now become dependent on the charge power and the time that is available for charging. Calculations show that the charge powers that are needed at every stop are 1200 kW. The total minimum capacity on-board is 251 kWh. With the available weight of 5310 kg this results in roughly 226 W/kg and 47 Wh/kg. This result is plotted with a blue dot in figure 5. Current lithium- ion battery technology is still not ‘spot on’ but taking into account the various ‘tuning buttons’ that the designer can play with in the upcoming detailed simulation, it is decided to proceed with Lithium-ion batteries as ESD, and a combination of overnight and intermediate charging as charging strategy.

4. DETAILED MODEL DESCRIPTION

MATLAB/Simulink is chosen for the simulation of the benchmark and the above selected ESD configuration. The preliminary simulation models consists of a combination of in-house component models and component models that have been developed in the JOULES project. Further development of the simulation models is ongoing, but nevertheless a brief description and some preliminary results are given here. Figure 11 gives a general overview of the model structure and its components.

4.1 HULL AND SHIP DYNAMICS

The resistance of both the benchmark and alternative configuration vessel are kept similar. It is assumed that displacement changes have no influence on the resistance. The resistance is represented as a simple resistance curve. Both thrust deduction and wake fraction remain constant over speed. The interaction between propeller thrust and ship resistance is captured in differential equation 6-1 where *m*, the displacement of the vessel, is kept constant.

$$F = m \cdot \frac{dv}{dt} \quad \Rightarrow \quad \frac{dv}{dt} = \frac{F_{in} - F_{out}}{m} \qquad (6\text{-}1)$$

This approach is very simplistic as no manoeuvring is introduced in the model. It is chosen to keep this simple approach since no real data about manoeuvring is available other than that manoeuvring in the operational profile is very limited.

4.2 PROPELLER

The propellers used for both the benchmark and the alternative configuration are modelled with the use of standard series data from the Wageningen B Propeller Series of which the coefficients from equation (6-2) are taken from [4] and the propeller properties are kept similar to the benchmark model.

$$\begin{aligned} K_Q &= \sum_{n=1}^{47} C_n \cdot (J)^{S_n} \cdot \left(\frac{P}{D}\right)^{t_n} \cdot \left(\frac{A_E}{A_O}\right)^{u_n} \cdot (z)^{v_n} \\ K_T &= \sum_{n=1}^{39} C_n \cdot (J)^{S_n} \cdot \left(\frac{P}{D}\right)^{t_n} \cdot \left(\frac{A_E}{A_O}\right)^{u_n} \cdot (z)^{v_n} \end{aligned} \qquad (6\text{-}2)$$

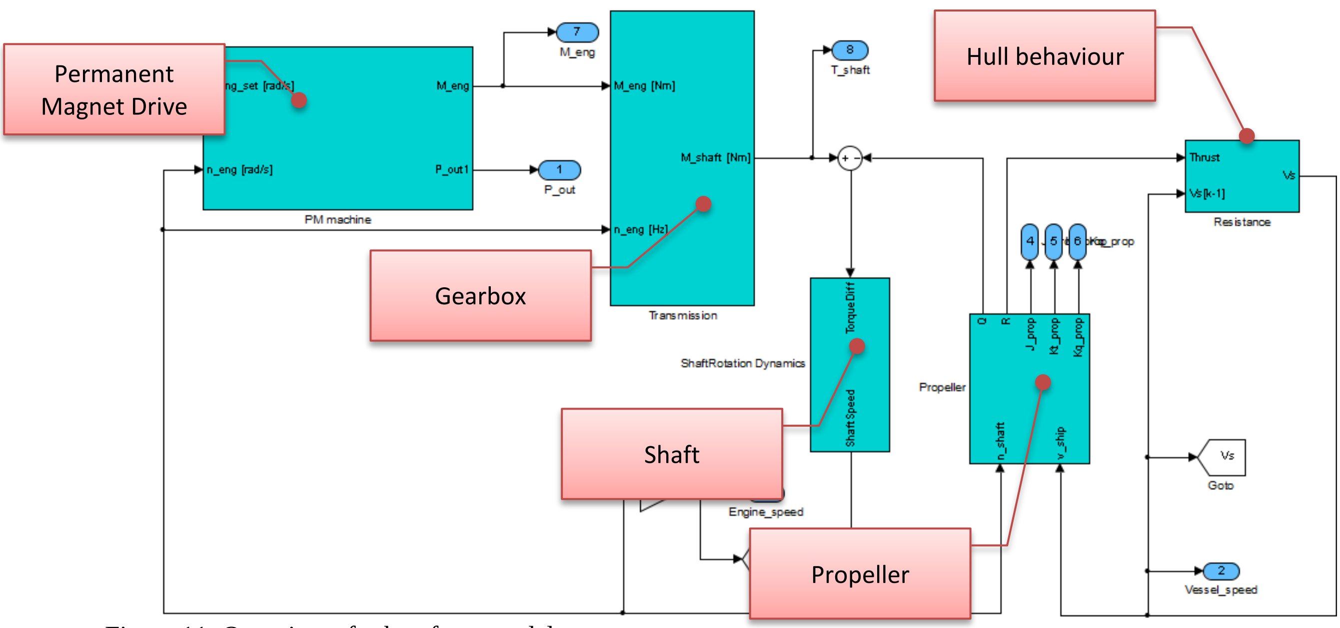

Figure 11: Overview of urban ferry model components

The propeller design remains unchanged for two reasons;

- the calculated open water efficiency (η_o) of the benchmark propeller at a constant operating speed of 40 km/h is quite high at η_o = 0.66. Gains by alternative propulsors are expected small and are, as this thesis focuses on a total propulsion configuration, negligible.
- the fact that the propeller operates at a relative high speed (920 rpm), means that a high speed electric machine with gearbox can be placed which has beneficial specific power compared to a low speed electric machine.

4.3 SHAFT AND TRANSMISSION

The transmission efficiency can be approximated with gearbox and shaft loss models based on [5]. The mechanical torque difference between the supplied torque via the shaft and the demanded torque from the propeller is captured in equation 6-3. In this differential equation the inertia of the system is assumed constant.

$$M = I \cdot \frac{d\omega}{dt} \quad \Rightarrow$$
$$\frac{dn}{dt} = \frac{1}{2 \cdot \pi} \cdot \frac{d\omega}{dt} = \frac{1}{2 \cdot \pi} \cdot \frac{M_{in} - M_{out}}{I} \qquad (6\text{-}3)$$

4.4 'FMU' COMPONENT MODELS

Various component models are not discussed in detail here. The main reason is that the models used for these components are build up as Functional Mock-up Interfaces (FMU) making the detailed modelling structure invisible for the user. This means that those components cannot be modified and only used as *black box* building blocks. The reason for this interface is mainly the preservation of knowledge when sharing model components between parties within the JOULES project. The battery model, figure 12, is one of the model components received from a JOULES partner that was implemented as a FMU.

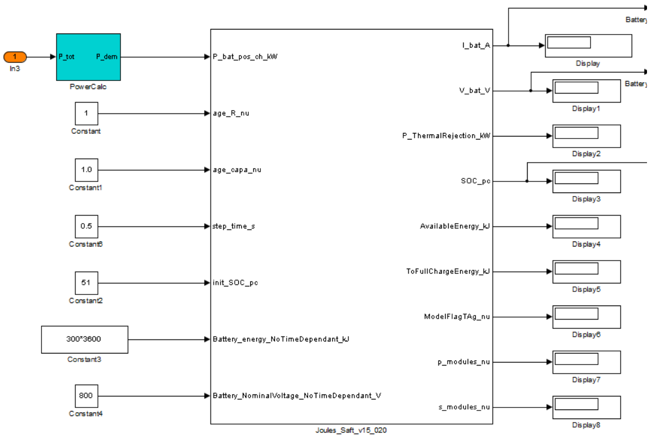

Figure 12: FMU format battery model as received from a partner in the JOULES project.

5. PROCESSING RESULTS

In this section several simulations are presented and discussed. The full ESD configuration is modelled with the components described in the previous section. For this configuration several operational scenarios will be run to analyse the effect on the energy flow and state of charge (SoC) of the batteries.

5.1 SIMULATION RESULTS

Firstly the full electric configuration is simulated for one run without shore charging power. A 479 kWh battery pack is installed based on the available weight and energy density requirement. Figure 13 shows the simulated speed profile and total distance sailed. The vessel is able to sail the single run in nearly 59 minutes. Figure 14 shows the energy delivered by the battery which is for one run 292 kWh. In one run the battery SoC has dropped from a full battery (SoC = 1.0) to 0.41.

If shore power is applied at every stop, and the power from shore is assumed unlimited in terms of maximum power, the limiting factor would be the C-rate of the battery. Since the manufacturer advises a charge rate of

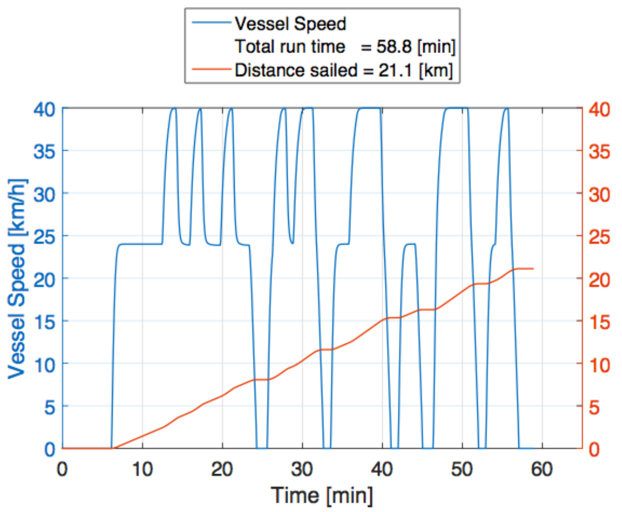

Figure 13: Speed and sailed distance plot

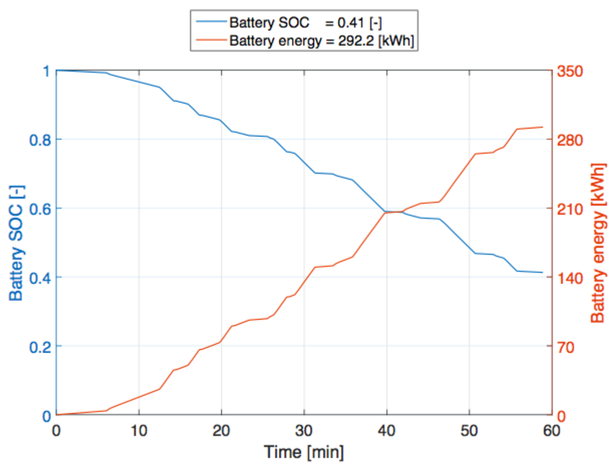

Figure 14: Total energy and SoC plot

0.5 C, the maximum shore power is set at 250 kW accordingly. The result of using shore power is that the total net energy drawn from the battery becomes less, resulting in a higher SoC after one run. This is visualized in figure 15, where the SoC at the end of the run is 0.47. The total net energy drawn from the battery is 263 kWh.

The benchmark vessel sails 15 runs a day. If the Full ESD configuration is subjected to this profile, including the proposed shore power of 250 kW at stops, the simulation is stopped after roughly 90 minutes, as can be seen in figure 16. At that time the battery has reached a SoC of 0.15 which is a minimum value in the simulation. This means that in reality the ship could sail 1,5 hours, covering a distance of roughly 33 km.

Based on the preliminary time domain simulation, it can be concluded that with the initial applied battery capacity it is not possible to sail a return trip from Rotterdam to Dordrecht, therefore the battery capacity should be increased.

5.2 BATTERY CYCLE LIFE

The conclusion in the previous section can be drawn without even considering the cycle life of the batteries. For a next cycle in the design spiral this should however be considered. It is already known that battery packs need to be replaced multiple times in the vessel lifetime.

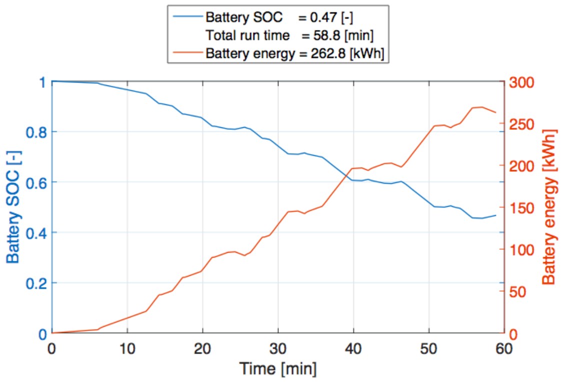

Figure 15: Net battery energy and SoC with shore charging at every stop with 250 kW

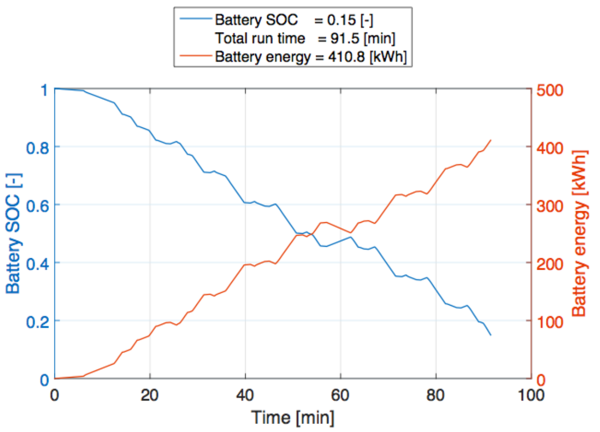

Figure 16: Net battery energy and SoC with shore charging at every stop with 250 kW full run

Depending on the exact usage, battery lifetime will be 2-5 years where a comparable size diesel driven propulsion train only needs significant component replacement every 12-17 years. For a reasonable trade-off analysis between different propulsion trains the lifetime should be determined more in detail. [6] gives a good description of the main parameters influencing the lifetime of batteries being mainly:

- charge and discharge rate (C-rate),
- depth of discharge,
- operating temperature,

of which the first two are already included in the model so far. Modelling temperature behaviour of the batteries on cell level is still under development and will be implemented in the coming months. The current result of a simulation run are graphs as figure 16, showing the SoC over time. The *rainfall* methodology as made applicable in [7] will be used to convert the SoC over time to a battery lifetime.

5.3 INPUT VARIATIONS

The results as presented in this chapter are the outcomes of a first design step. Changes can be made to the operating profile, the battery selection, and to the ship as part of next iterations in the design process. To evaluate the effect of such variations the use of a simulation model proved of important value. Some of the important variations that are under consideration are:

- What would be the effect of an extra stop (=charging time) along the route?
- What would be the effect of sailing at reduced maximum speed?
- What would be the effect of increasing the stop time at hubs?
- What would be the effect of lengthening of the vessel to allow for carrying more ESDs?
- What would be the effect of using different batteries ?

Because the evaluation of these options is still ongoing, no further results will be presented here. Instead of this, a critical view is given on the approach as described in this paper.

6. CONCLUSIONS

Based on the outcome of the simulations so far, some conclusions can be made.

- ESD selection based on the Ragone plot is sufficient for an initial selection only. When more detailed simulation of the ESD in specific operational profiles is performed, it can be seen that actual performance cannot be judged by power and energy density alone. Already a relatively basic battery model shows that the battery design size is highly dependent on the exact operational profile in combination with charging strategies.

- In initial powering calculations done by Damen acceleration and deceleration are not included since they are not a limiting factor for diesel driven propulsion trains. For battery applications it is found that acceleration and deceleration have significant influence on the energy usage. Load changes are a big part of the operational profile of the urban ferry as discussed in this paper and therefore this point has to be included in the analysis.
- As mentioned in the conclusion of the previous chapter, no battery life analysis results are presented yet. Since battery replacements have significant effect on lifetime expenses which is important for customers, this will be important for a holistic alternative ESD analysis.

The general conclusion that can be drawn is that the evaluation of concept of most non-conventional energy storage devices and their power plants cannot be performed without a thorough simulation study considering the complete list of judgment criteria as explained in section 3.1. Where some of the criteria can be chosen based on relatively straight forward calculations, most of them demand an extensive simulation to be able to determine their performance realistically.

7. SIMULATION IN A DESING PROCESS

The final goal of projects related to alternative ESDs is that they merge into a workflow that is implemented in the Damen design process. The current design process is probably best visualized by the design spiral in its different forms as described by [8], [9] and [10]. In the 'ideal' design process subsequently the different design 'stations' are being evaluated, increasing precision with every design 'loop'. Ideally, for every design station, methods are available that support the designer in the different precision levels; from an initial estimate in concept design phase up to the detailed design phase. Focussing on concept design phase, a tool should not necessary give a very precise estimate, but sufficient precision for an initial design iteration. E.g. a quick speed prediction in a very early stage of the process will generally be within 15-25 % from the final solution.

This design philosophy is mainly based on propulsion systems involving conventional power and propulsion systems. If revolutionary energy concepts are applied that consist of ESDs with properties as explained in this paper, the conventional design approach does not provide the appropriate tools and workflow for a proper design consideration. As shown before, a rapid design exploration solely based on a Ragone plot does not even give enough accuracy for concept design phase. Small design choice changes in e.g. the charging strategy have significant influence on the final outcome of the design.

Being one stop in a comprehensive design process it is necessary to be able to make an initial estimate with enough certainty in a reasonable amount of time. Describing at least a clear process summarizing required input, a timeline and a working procedure to process the simulation results performance indicators makes it possible to merge this step in the total design loop in the future. This work needs to be done when initial studies for the JOULES project are finalized and Damen decides to develop the methodology further for future client cases and actual projects.

8. FUTURE VIEW

This work is a first exploration on alternative ESD implementation within high speed craft design. Since the application of alternative ESDs is relatively new to the maritime industry, it is expected that the long term properties of these ESDs will more and more be known. As a result, it is expected that in the future more straight forward methodology will become available that make the concept exploration easier and quicker. Furthermore, tools like the Ragone plot will evolve together with the development of the different ESDs so constant updates will be necessary. For now, the workflow as used for the described project is 'the best we have' and it needs some fine-tuning while applying it to current and future design cases, and step by step it will be improved in close consultation with the designers. After a few projects the applicability of this method as tool for designers should be evaluated critically.

9. ACKNOWLEDGEMENTS

The work leading to this invention has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 605190.

10. REFERENCES

[1] JOULES. (2015). Urban Ferry Application Case. Retrieved June 25, 2015, from JOULES Project Website: http://www.joules-project.eu/Joules/application_case/ferry/urban%20ferry

[2] Degroote, D., & Koperen, R. v. (2014). Fuel Economy: Hybrid Solutions and Beyond. ITS. Hamburg.

[3] Ragone, D. (1968). Review of Battery Systems for Electrically Powered Vehicles. SAE Technical Paper 680453.

[4] Carlton, J. (2010). Marine Propellers and Propulsion (Third Edition). Butterworth-Heinemann.

[5] Stapersma, D. (1994). The Importance of (e)Mission Profiles for Naval Ships. INEC 94, Cost Effective Maritime Defence.

[6] Omar, N. e. (2014). Lithium iron phosphate based battery – Assessment of the aging. Applied Energy 113, 1575-1585.

[7] Johannesson, P., Brodtkorb, P., Lindgren, G., & Rychlik, I. (2011). WAFO - a Matlab Toolbox for Analysis of Random Waves and Loads. Lund: Mathematical Statistics, Lund University.

[8] Evans, J. (1959). Basic Design Concepts. Naval Engineers Journal, 671-678.

[9] Buxton, I. (1972). Engineering economics applied to ship design. Transactions of RINA 114, 409-428.

[10] Andrews, D. (1981). Creative Ship Design. Transactions of RINA 123, 447-471.

11. AUTHORS BIOGRAPHY

Deniz de Koningh MSc holds the current position of development engineer at the Damen Shipyards Group. He is responsible for supporting the company with developing new vessels, realized by providing them advice based on state of the art technologies and developments in shipbuilding industry. His previous experience includes high speed craft and passenger ferry design and a study in Naval Architecture at Delft University of Technology with specialty Ship Design.

Arthur Vrijdag PhD graduated from the Royal Netherlands Naval College in 2004 and in the same year he obtained his MSc degree in ship hydromechanics at Delft University of Technology. In 2009 he finished his PhD research at the same university and started working at Rolls-Royce Naval Marine in Bristol, the UK. In 2011 Arthur started at the R&D department of Damen Shipyards where he was active as Project Manager for the JOULES project. Since September 2015 he works as assistant professor at Delft University of Technology in the Marine and Transport Technology department.

Henk Jan Bosman MSc graduated at the Marine Engineering department at Delft University of Technology. During his graduation period at Damen Shipyards Gorinchem he performed his thesis called Future Urban Ferry, a conceptual study using zero-emission energy storage devices. The aim of this thesis was to investigate whether energy storage devices can be used in order to reduce local, harmful, polluting emissions of an urban ferry. This was investigated by modelling zero emission energy storage devices in a power and propulsion configuration.