Master Thesis

Supercapacitor energy storage for load levelling on board of diesel-electric yachts

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Thesis for the degree of MSc in Marine Technology in the specialization of Ship Design and Fundamentals of Marine Engineering

Supercapacitor energy storage for load levelling on board of diesel-electric yachts

By

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Performed at

Feadship

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Introduction

Feadship is continuously searching for opportunities to improve their yachts. Firstly, this chapter will discuss the challenges that are introduced by the implementation of lithium-ion batteries in the frequently used diesel electric propulsion set-up and by installing more sustainable prime movers, than the diesel generator. Secondly, it will discuss how an alternative energy storage system (ESS) can offer a solution in these challenges. From this problem definition the main and sub research questions will be derived.

1.1. Lithium-ion batteries for load levelling

Feadship is currently using two types of drive trains in their yachts. The diesel direct and the diesel electric drive train. The diesel direct drive train,Figure 1.2 features a physical drive shaft between the main engine and the propeller. The diesel electric drive, Figure 1.1, train has multiple diesel generators connected to an electrical grid from which the propeller is powered. The diesel electric drive train can be favoured over the diesel direct drive due to the versatility of the propulsion plant with regards to operating points [1] [2]. The presence of multiple generators connected to the same electric grid, increases the time in which they can operate in their most efficient regime. This can even be enhanced by installing an energy storage system, like lithium-ion batteries. For instance, when the diesel generator operates at it's most efficient working point, but does not match the required power, the excess or shortage of energy can be stored in or supplied by the battery [3]. Since yachts engage in many modes of operation, this leads to an overall increased efficiency compared to the diesel direct driven yacht [4] .[1] Besides, the use of an ESS enables load levelling in which load fluctuations can be levelled by means of storing and supplying energy with the ESS, which requires less power adjusting from the prime mover.

However, battery use does not come without disadvantages. Firstly, batteries suffer from capacity degradation when running through cycles [6]. Therefore, the continuous charging and discharging in the diesel electric operation can be a burden. The more the batteries are used to increase system efficiency, the more degradation is introduced. Once the battery capacity drops below a certain treshold, they need to be replaced. This introduces costs and an additional environmental impact for battery production. Secondly, batteries perform excellent with regards to energy density, but have limited power density [7], which currently leads to voluminous and heavy battery packs. Lastly, the use of batteries comes with charge and discharge losses, which are not introduced by powering the propeller without intermediate energy storage [7].

1.2. Alternative prime movers

To meet future regulations with regards to emissions, it is likely that alternative prime movers will be used in the future. Gas engines or fuel cells are examples of these. Compared to diesel engines and generators these often underperform with regards to delivering fluctuating power, since the power

[1] Note that the diesel direct propulsion will be more energy efficient at its design speed, since there will be no electric conversion losses of around 10% [5]

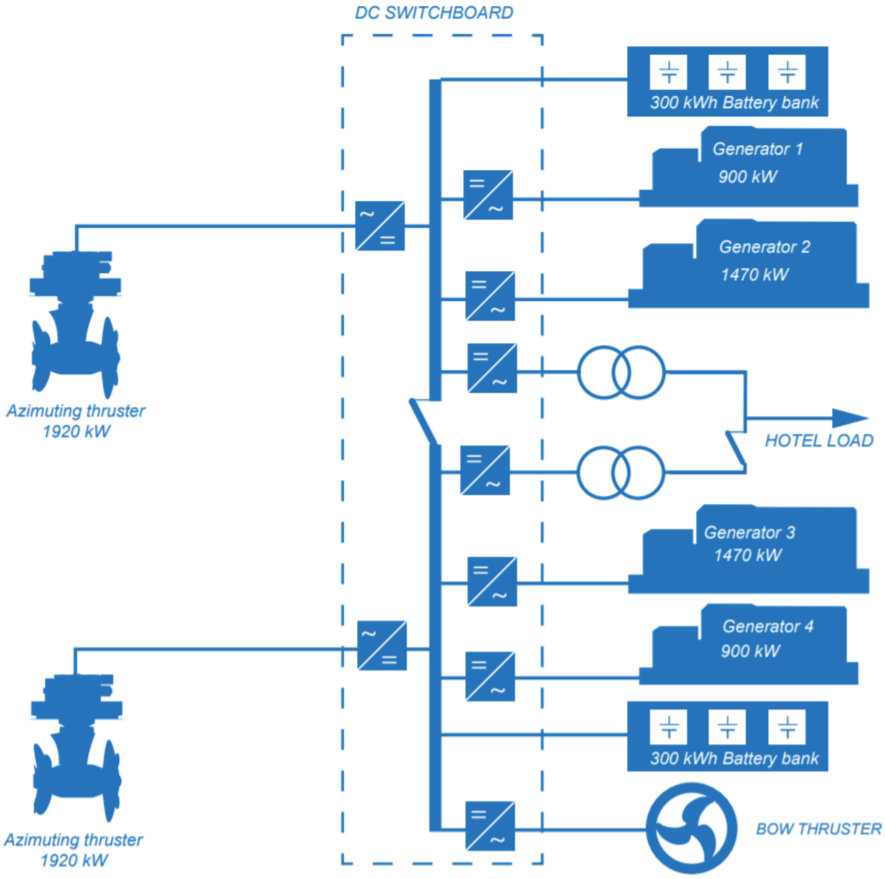


Figure 1.1: Diesel electric propulsion set-up

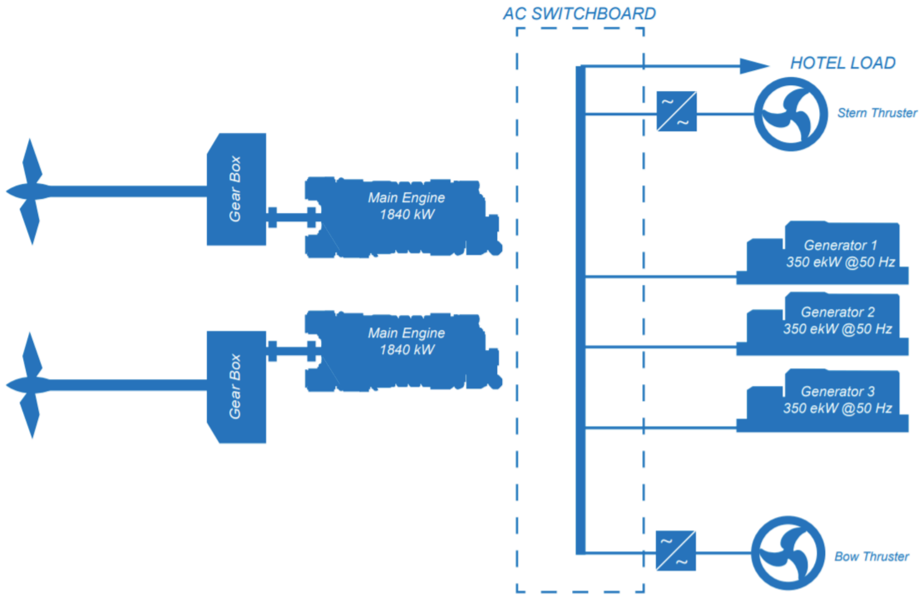


Figure 1.2: Diesel direct propulsion set-up

adjustment takes more time. This means the future prime movers might not be able to meet the raw power demand variations by the propeller. Therefore, a future proof propulsion plant will likely require some type of power demand treatment in order to fit the performances of the prime movers.

An ESS can be used for minimising these load fluctuations by means of load levelling. During high power demand the ESS will supply energy by acting as a voltage source on the DC-grid. During low power demand the ESS will store energy by charging on the DC-grid voltage. The ESS will help stabilise the grid voltage and the prime mover will 'feel' less of the load fluctuations that are imposed by the propeller, which means a prime mover with lower transient behaviour capabilities than a diesel generator can be selected.

1.3. Problem definition

Currently, Feadship is facing two challenges. Firstly, the use of batteries in the diesel electric propulsion system, which will improve the system efficiency, introduces battery capacity degradation. Secondly, the implementation of more sustainable prime movers might not be as simple as just replacing the present day diesel generators, since the transient behaviour performance will deteriorate. This might introduce the need to additional load levelling to stay within the limits of the prime mover.

In order to tackle these issues Feadship wants to explore the use of an additional energy storage system. This objective can be divided in three parts. Firstly, the effect of using an additional ESS on the battery load will be investigated. Which part of the load will be transferred from the batteries to the additional system? Transferring load from the batteries to an alternative system will lead to a reduction in battery capacity degradation and an increase in battery lifetime. Secondly, an evaluation of the total energy storage system size will be made. Which weight and volume reductions can be achieved by replacing a part of the batteries by another energy storage system? Potentially, a smaller system, when selecting the right alternative ESS, can lead to similar or improved operational behaviour. Finally, the performance of the system will be evaluated. Will the system deliver the demanded power and how is the prime mover power demand influenced? If the introduction of an additional ESS reduces the transient behaviour for the prime mover it could be a solution for the introduction of future prime movers.

Prior to this research the literature research '*Comparing different energy storage methods for load levelling on board of diesel electric yachts*' has been performed. Based on the power consumption of a yacht and the available energy storage systems it was determined that a supercapacitor would be used as additional ESS for levelling wave induced load fluctuations. For an extensive explanation with regards to this choice chapter 2 and Appendix D can be consulted.

In order to evaluate the use of supercapacitor energy storage, a propulsion plant time domain analysis model will be set up. This model will be used in order to make an evaluation which can supplement the static calculations by giving insight in the operational behaviour of the system over time.

1.4. Research questions

Based on the aforementioned the following research question will be answered:

How can levelling wave-induced load fluctuations in yachts with supercapacitor energy storage contribute to battery capacity preservation and downsizing of the propulsion plant?

A simplified power demand analysis is used in the literature research. This data was sufficient for selecting a supercapacitor as energy storage system and the wave loads as the loads to be levelled. However, for the time domain analysis a more realistic and specific data set is required. This leads to the following sub-questions:

1. *How does the propulsive power demand of a yacht sailing in waves look like?*

2. *How can propulsive power demand data be implemented in a yacht propulsion plant model?*

Analysing the propulsive power demand of a yacht sailing in waves will create more insight in the characteristics of the signal. This can be used to further specify the propulsion plant requirements for this research. Before conducting the simulations an overview of the ratio between supercapacitors and batteries, the type of supercapacitor and the implementation in the propulsion plant should be known. This leads to the following sub-questions:

3. *Which type and sizes of supercapacitors will meet the requirements for levelling the wave loads?*

4. *How are the supercapacitors implemented in the electrical grid of the propulsion plant?*

In order to get insight into the performance of the modified propulsion plant a time domain model is used. This model will simulate propulsion plant operation during sailing. Two main design considerations have to be made for this. The first regards the model architecture. It should be considered which plant components should be included and how they are connected. The second regards the energy management strategy. This will regard how the system components interact and how the power plant will behave when the power demand changes. This leads to the following sub-questions:

5. *Which model components must be included in order to set up a propulsion model of the desired level of reality?*

6. *Which energy demand strategy is most suited for the evaluation of an additional energy storage system on board of yachts?*

Lastly, the propulsion plants must be compared in order to evaluate the performances. Simulation output that can be used as evaluation criteria should be considered. Three different evaluation criteria will be used. Firstly, the battery load, which takes into account the use of the batteries during sailing in waves. Secondly, the plant geometry, which takes into account the impact on design. Lastly, the plant behaviour, which takes into account the power demand for the prime mover. This leads to the following sub-question:

7. *Which simulation output can be used to evaluate the propulsion plant configurations?*

1.5. Chapter overview

In chapter 2 an overview of the literature research '*Comparing different energy storage methods for load levelling on board of diesel electric yachts*' will be given. This elaborates upon certain research decisions that have been made. An example of this is the choice of ESS. In chapter 3 the methodology for this research is explained. In chapter 4 the power demand data is discussed. This includes the selection, pre-processing and intentional omission of data. In chapter 5 the power demand data is analysed. Based on this analysis a specific supercapacitor is selected. Also the required energy capacity is based on this analysis. In chapter 6 the time domain model will be discussed. Both the components included and the energy management strategy will be discussed. In chapter 7 the results of the time-domain simulations will be discussed. In chapter 8 the added value of a supercapacitor bank and the propulsion plant performances will be discussed. In chapter 9 the matter that requires more attention in later research will be discussed in order to get a complete overview of the use of supercapacitors as additional energy storage system on board of yachts.

2

Literature research summary

Prior to this research the literature research *Comparing different energy storage methods for load levelling on board of diesel-electric yachts* has been performed in order to identify knowledge gaps in the area of load levelling in yachts. This chapter will summarize the subjects that are essential for full understanding of this research. For the full length literature review Appendix D can be consulted.

2.1. Propulsion plant

As mentioned in chapter 1, Feadship is currently using two types of drive trains in their ships. However, the diesel electric set-up is becoming increasingly common. The main reason for this is the increased efficiency for the overall operational profile compared to the diesel direct propulsion plant. Therefore, the diesel electric set-up will be used in this research.

2.2. Power demand

Sailing and hotel loads in a yacht both account for around 50% of the fuel consumed. Therefore, both operational modes are evaluated for the application of an ESS. Several methods for determining the power demand of a yacht have been set up.

In the first method the power use of each electrical consumer on board was analysed. By adding all the data an overall yacht power demand could be set up. However, due to the lack of dynamic data this method was not suited for the evaluation of an additional energy storage system for load levelling.

The second method was to use the measured power consumption on board of full scale yachts. However, due to limited available data the research would become highly dependent on one ship. This would make the research less usable for a range of vessels. Nevertheless, this data could be used for a first evaluation of the duration and magnitude of power fluctuations in the hotel loads and propulsive loads in calm waters.

In the last method, the propulsive power fluctuations encountered during sailing in waves are derived by logging the shaft power during model seakeeping tests performed by MARIN.

An analysis of the full scale yacht data and the data that was acquired by MARIN gave insight into the encountered power fluctuations for the hotel loads and the propulsive loads for sailing in calm water and waves. Both the durations and the magnitudes of fluctuations were determined. The results are shown in Table 2.1. The relatively small amplitude of propulsive power fluctuations when sailing in calm waters would require neither high battery power nor significant ramping by the prime mover for load levelling. Since sailing in calm waters is not the most critical operational condition with regards to power fluctuations, it was decided to not include it in this research. Nevertheless, an additional ESS that is designed for a more critical operational conditions could still offer benefits during sailing in calm waters.

2.3. Energy management

Two methods of energy management were discussed: rule-based control (RBC) and the equivalent consumption minimization strategy (ECMS). In RBC the system functions by a set of rules, whereas

	Duration [s]	Rel. magnitude [%]
Hotel loads	100	10-20
Propulsive loads calm water	17	<5%
Propulsive loads waves	7	15-25

Table 2.1: Power fluctuation duration and relative magnitude for various operational conditions

ECMS uses a cost function upon which system operation is determined. This function determines the cost of certain operations in order to get the most desired system behaviour. RBC guarantees system functioning in a clear and non-complex way. The ECMS is more complex than RBC, but can give a better approach of the the optimal solution than RBC. In the main research RBC is favored over ECMS, due to the low complexity and the fact that RBC is deemed appropriate for modelling a yacht power plant to the required level of detail. Besides, ECMS is especially useful for limiting the emissions and fuel consumption, which is not the goal of this research [8] [9] [10].

2.4. Prime movers

Diesel generators or engines are characterized by their ability of coping with transient loads. They will usually outperform gas engines and fuel cells. However, in order to meet future regulations [11] the switch to alternative prime movers is likely. Therefore, it is useful to lower the amount of fluctuations in order to prepare the power demand in order to facilitate the use of future prime movers with inferior ramping capabilities.

2.5. Energy storage systems - ESSs

Currently, batteries in Feadships are often designed based on the power output. However, often this leads to a higher energy capacity than needed for proper operation. Preventing this energy (or in some cases power) surplus can be done by optimising the energy storage system for the power-over-energy-ratio. Since the energy capacity is related to nominal power output over a certain duration, this ratio is time dependent. Therefore, the power-over-energy-ratio corresponds to the discharge time of an ESS, also known as the C-rate in batteries. In other words, if the batteries introduce an energy capacity surplus the battery C-rate is lower than the vessel requires. It was deemed that optimising for the power-over-energy-ratio would lead to a weight and volume reduction for the ESS, compared to batteries.

In line with the aforementioned the hotel load fluctuations and the propulsive load fluctuations require an ESS with a C-rate of 36 and 514. These values correspond to ESSs that can fully discharge in 100 and 7 seconds at nominal power. Figure 2.1 shows the power and energy density of multiple ESSs. The diagonal lines in this figure represent constant power-over-energy-ratios. It can be seen that potential systems for these fluctuations are the supercapacitor (SC), the flywheel (FW), the superconducting magnetic energy (SMES) and li-ion battery (B) energy storage. Due to the safety objections associated with flywheel energy storage in transport applications and the low power and energy density of superconducting magnetic energy storage these are excluded from the research. Besides, batteries are not considered as additional energy storage system, since the goals is to limit battery use. The supercapacitor performed great in terms of C-rate, safety and degradation. In contrary to batteries supercapacitors do not show any degradation. Therefore, supercapacitors could be a potential replacement for part of the battery pack in order to limit battery degradation [7].

2.6. Supercapacitor working principle

Supercapacitors store energy in an electrochemical way, whereas batteries store it in a chemical way. This leads to a higher power density, but a lower energy density for supercapacitors compared to batteries. When supercapacitors are placed in a DC grid the current induces a potential difference over the two conductors. Once the grid voltage drops the supercapacitor can act as a voltage source, until the potential difference is cancelled. By voltage regulation a supercapacitor can be used as an ESS [7][12][13].

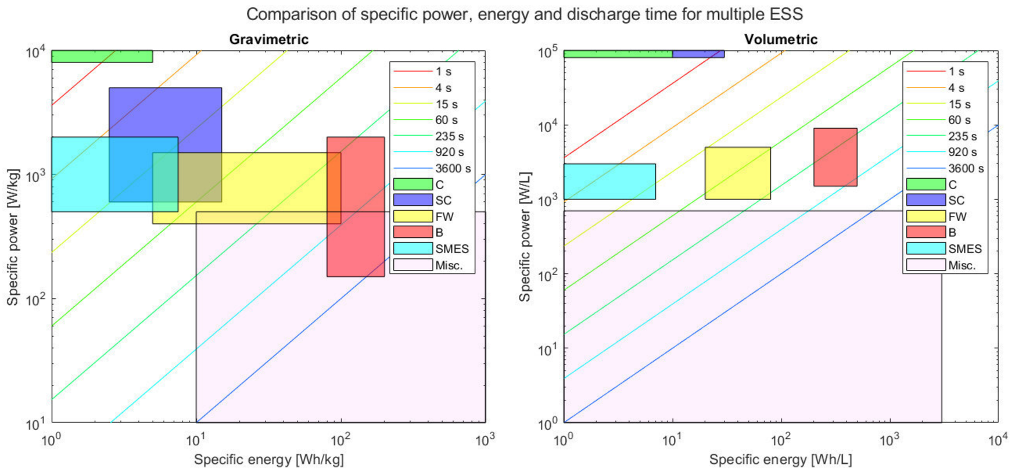


Figure 2.1: Gravimetric and volumetric densities [7]

2.7. Conclusion

The yacht power demand has been separated into three different categories. The hotel loads, the propulsive loads in calm water and the propulsive loads in waves. Each type showed fluctuations of different durations and amplitudes. In order to prevent these fluctuations from leading to battery capacity degradation or excessive prime mover ramping, an additional ESS can be implemented.

In order to optimise for the size of an additional ESS while still maintaining proper load levelling capabilities, the additional ESS should be matched to the specific fluctuations. Longer durations require energy dense ESSs. Shorter durations require power dense ESSs. According to this reasoning, levelling the hotel loads and the propulsive loads in waves should be done with respectively lithium-ion batteries and supercapacitors. Since the aim of this research is to limit battery capacity degradation and reduce the plant size, it was decided to investigate levelling wave-induced load fluctuations with a supercapacitor.

3
Methodology

The supercapacitor energy storage will be evaluated by means of a time domain analysis. A model of a yacht propulsion plant will be used for this. The main components that contribute to yacht propulsion will be included, which are:

- Prime mover
- Lithium-ion battery bank
- Supercapacitor bank
- Electric motor powering the propeller

This model requires input in the form of power consumed over time by the propeller, which is explained in section 3.2. In order to compare system behaviour, multiple combinations of battery and supercapacitor power will be installed, which is explained in section 3.3.

3.1. Propulsion plant model

The propulsion plant model will be used to simulate a yacht sailing in waves. A load case consisting of seakeeping test data from MARIN will serve as input. How this data is acquired is explained in section 3.2. The supercapacitor type and the different plant configurations will be included as part of the model. How the different configurations are determined is explained in section 3.3. With the assistance of RH Marine the essential propulsion plant components will be selected. Subsequently, a simplified energy management strategy will be determined, which is suitable for evaluating the added value of the configurations. The simulation results will include the amount of power that is delivered by both of the ESSs and the average ramp rate of the prime mover. Based on these values the conclusions will be set up.

3.2. Power demand data and time factors

For the collection of propulsion power demand data multiple options have been considered. Setting up the data by means of a consumer list, using data from actual measurements and using data from model tests. The latter is most extensive, reliable and best monitored with regards to the environmental conditions. Therefore, the shaft power data from the seakeeping tests from MARIN will be used as input for the propulsion plant analyses. If required, this data will be pre-processed.

The output of this will be a series of power demand data for several wave heights and periods. This data will be suited for performing simulations for the corresponding wave height and wave period. However, the environmental conditions in this data set do not have the same chance of occurrence when considering an actual vessel. Therefore, vessels with operational area A, B and C are identified among the Feadship fleet. Based on the corresponding scatter diagrams a vessel type is selected for the supercapacitor energy storage evaluation.

The wave scatter diagram and the shaft power data will be combined into a load case definition, by means of assigning time factors to each time trace.

3.3. Supercapacitor specification

The power fluctuation energy and duration in the combined load case will be analysed. Based on this a supercapacitor will be selected. Also an estimation of the required energy capacity will be made. This will be used to determine multiple plant configuration in which a varying amount of supercapacitors is installed. The weight and volume savings of each plant configuration will be the first results and lead to the conclusions. Next, each of the plant configurations will be evaluated in the simulations. This will give insight into the change in battery use and ramping behaviour of the prime mover when supercapacitor energy storage is used.

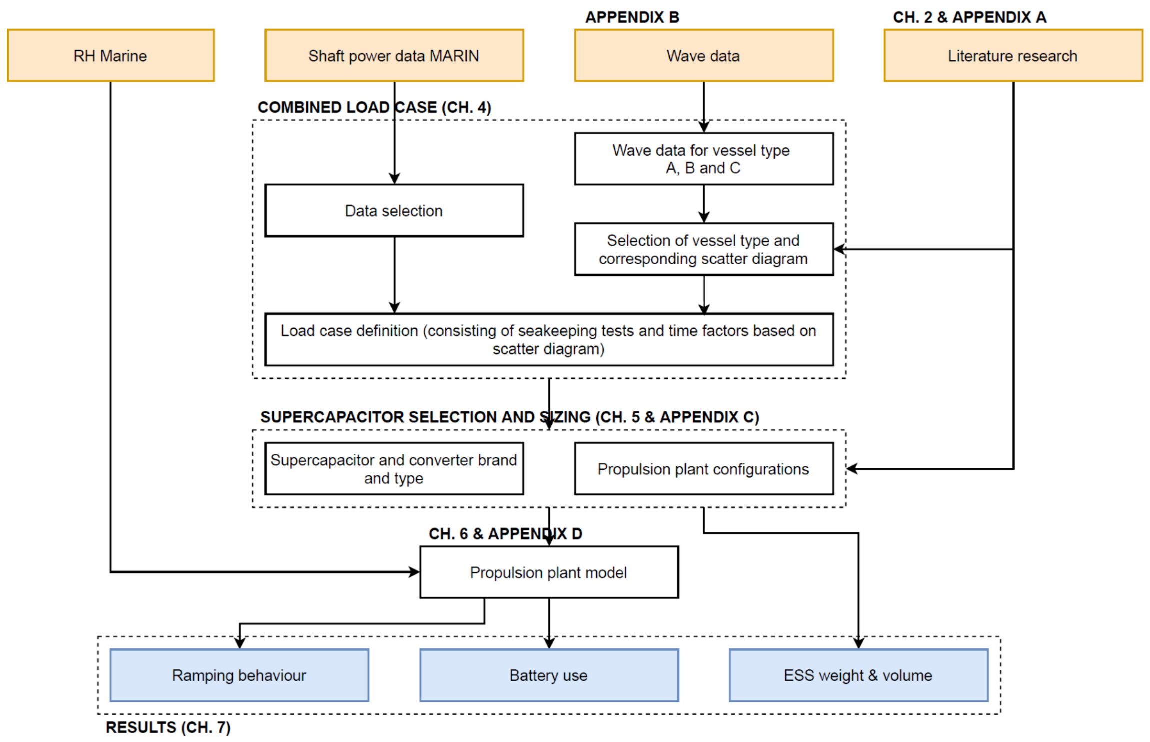


Figure 3.1: Flow chart of research methodology

4
Load profile definition

A series of power consumption time traces will function as input for the simulations. These power consumption time traces will be based on seakeeping test data from MARIN. This chapter will discuss which tests have been performed, what data is available and how the data will be preprocessed in order to be useful for this research.

4.1. Seakeeping tests MARIN

For the design of a 100+ meter yacht, MARIN has performed various seakeeping tests. During these tests a self propelled model is equipped with measuring systems, which were used to collect time traces of various parameters. Included are, among others, the ship motions, propeller thrust, shaft rpm and shaft torque. In Table 4.1 an overview of the test conditions is shown.

Test nr.	Heading [deg]	Wave height [m]	Wave period [s]	Model speed [kn]	Fins (active or passive)
314	180	1.75	10	18.8	A
315	180	2.5	10	15.1	A
316	180	4	10	13.3	A
310	135	1.75	10	18.7	A
311	135	2.5	10	15.0	A
312	135	4	10	13.2	A
313	135	4	7	12.4	A
322	285	1.75	8	18.4	A
320	300	2.5	7	14.6	P
321	300	2.5	7	14.6	A
317	315	1.75	7	18.4	A
318	315	2.5	7	15.0	P
319	315	2.5	7	14.9	A

Table 4.1: Test conditions seakeeping tests

4.1.1. Power calculation

The shaft power of the electric motors will serve as input for the simulations. Shaft power will be acquired by multiplication of shaft torque and shaft speed, as shown in Equation 4.1. Figure 4.1 shows the shaft power of a single propeller during the seakeeping tests.

$$P_s = T_s \cdot \omega_s \tag{4.1}$$

Please note the working envelope of the electric motors in the test set-up does not correspond to the working envelope of the full scale electric motors. The model electric motors are able to keep the shaft speed close to constant, whereas more fluctuations can be expected in full scale. Therefore, the case that is presented by MARIN will be conservative. However, no data is available with regards to the shaft speed variations for the corresponding full scale Feadship. This means the full scale fluctuations in torque and power might be smaller than claimed by the data. In chapter 9, this matter will be elaborated upon.

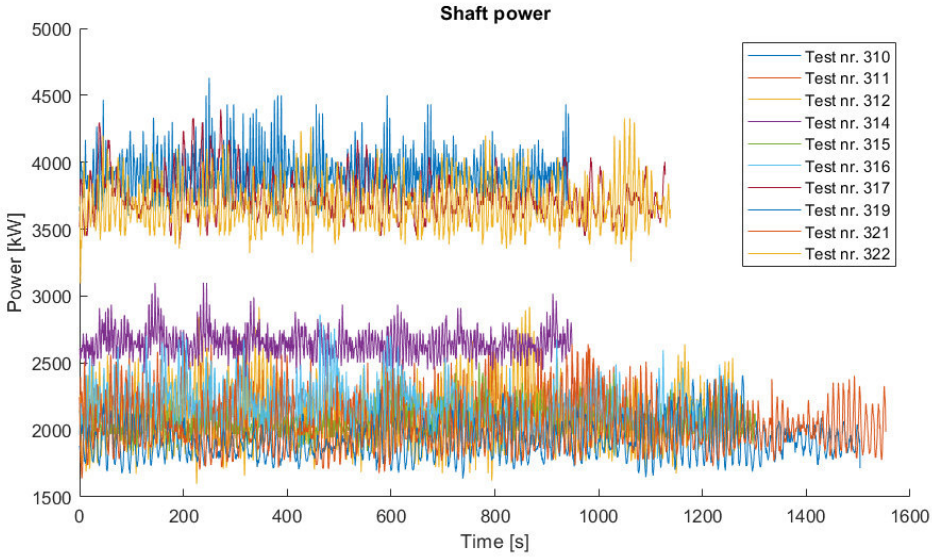


Figure 4.1: Power time traces during seakeeping tests

4.2. Load occurrence

Among the seakeeping tests are cases in extreme conditions. Since the application of a supercapacitor is not intended for incidental or emergency use the influence of these cases on the results should be kept to a minimum. A more reliable model input can be determined by using environmental data of areas where Feadships reside. The occurrence of certain wave conditions can be accomplished by assigning time factors to the seakeeping tests.

Table 4.1 shows the roll stabilization fins were engaged during most of the seakeeping tests, with the exception of test nr. 318 and 320. During regular operation the active fin stabilization on Feadships is usually engaged and will only be passive for a small part of the time. In order to set-up a load case that is as realistic as possible with the current seakeeping test data it is decided to not include test nr. 318 and 320. In addition, case 313 is disregarded, since the delivered power by the e-motors is significantly bigger than the power that can be delivered by the actual e-motors for the corresponding full scale vessel. Appendix B can be consulted for the shaft power time traces of test nr. 313, 318 and 320.

4.2.1. Ship types and sailing areas

Each Feadship is used differently and will encounter different environmental conditions. However, according to Akershoek [14] multiple categories of usage can be identified. Ships of type A mainly reside in the Mediterranean and North of Europe. Ships of type B mainly reside in the Mediterranean, Caribbean and Florida. They cross the Atlantic during autumn and spring. Ships of type C reside all over the world. However, they will still be located in Europe or North America for 65% of the time. Average yearly sailing distances for type A, B and C are respectively 7000, 10000 and 11500 nautical miles.

4.2.2. Wave spectra for sailing areas

In Figure 4.2, Figure 4.3 and Figure 4.4 the yearly average wave scatter diagrams for ship types A, B and C are shown. These diagrams are set up by taking the weighted average of the separate scatter diagrams for residing areas associated with these ship types.

	A	B	C
North Mediterranean	90%	35%	35%
Northe Europe	10%	10%	5%
Caribbean	0%	20%	10%
Florida	0%	25%	5%
North America	0%	10%	10%
Worldwide	0%	0%	35%
Yearly sailed mileage [nm]	7000	10000	11500

Table 4.2: Yacht residing areas

For type B the areas considered are the North Mediterranean, North Europe, Carribean, Florida and North America (as shown in Table 4.2). The assumption is made that these areas account for 90% of the sailed miles. For type C the scatter diagram accounts for 55% of sailed miles. This is due to the uncertainty which is introduced by the areas *North America* and *Worldwide*, since these areas cover multiple of the areas which are used by BMT in the global wave statistics [15].

	Wave scatter diagram						Annual, All Directions (Type A)					
Hs (m)	61	250	344	225	89	26	5	0	0	0	0	999
> 14	0	0	0	0	0	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0	0	0	0	0	0
12-13	0	0	0	0	0	0	0	0	0	0	0	0
11-12	0	0	0	0	0	0	0	0	0	0	0	0
10-11	0	0	0	0	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0	0	0	0	0	0
7-8	0	0	0	1	1	0	0	0	0	0	0	2
6-7	0	0	1	2	1	1	0	0	0	0	0	6
5-6	0	1	3	5	4	1	0	0	0	0	0	14
4-5	0	3	10	13	8	3	1	0	0	0	0	38
3-4	1	9	27	29	15	6	1	0	0	0	0	88
2-3	3	31	71	60	26	8	1	0	0	0	0	199
1-2	12	90	143	85	27	6	1	0	0	0	0	364
0-1	45	117	89	30	6	1	0	0	0	0	0	288
	< 4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	> 13	Tz (s)

Figure 4.2: Average yearly wave scatter diagram for ship type A

	Wave scatter diagram						Annual, All Directions (Type B)					
Hs (m)	28	141	260	254	168	89	39	14	4	1	0	999
> 14	0	0	0	0	0	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0	0	0	0	0	0
12-13	0	0	0	0	0	0	0	0	0	0	0	0
11-12	0	0	0	0	0	0	0	0	0	0	0	0
10-11	0	0	0	0	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0	0	0	0	1
8-9	0	0	0	0	0	0	0	0	0	0	0	1
7-8	0	0	0	1	1	1	1	1	0	0	0	3
6-7	0	0	1	1	2	2	2	1	0	0	0	8
5-6	0	0	1	4	4	4	3	2	1	0	0	19
4-5	0	1	6	10	11	9	6	3	1	0	0	47
3-4	0	4	17	29	28	19	10	4	1	0	0	113
2-3	1	16	53	72	56	30	12	3	1	0	0	244
1-2	6	52	115	107	57	21	6	1	0	0	0	365
0-1	21	67	66	31	9	2	0	0	0	0	0	197
	< 4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	> 13	Tz (s)

Figure 4.3: Average yearly wave scatter diagram for ship type B

4.2.3. Environmental conditions and potential ESS benefits

The ship type in which a supercapacitor will offer the most benefits depends on a multiple parameters. The wave height and wave period being the most important ones.

Firstly, a larger wave height will introduce bigger propulsive power fluctuations. Either, imposing transient behaviour to the prime mover or demanding more aggressive battery charge and discharge cycles. Both will be disadvantageous for the sustainability of the drive train. These processes will be most present in type B and least in type A. Since, as shown in Figure 4.5, waves heights of <1 m are

	Wave scatter diagram						Annual, All Directions (Type C)					
Hs (m)	46	201	314	248	125	47	14	3	0	0	0	999
> 14	0	0	0	0	0	0	0	0	0	0	0	0
13-14	0	0	0	0	0	0	0	0	0	0	0	0
12-13	0	0	0	0	0	0	0	0	0	0	0	0
11-12	0	0	0	0	0	0	0	0	0	0	0	0
10-11	0	0	0	0	0	0	0	0	0	0	0	0
9-10	0	0	0	0	0	0	0	0	0	0	0	0
8-9	0	0	0	0	0	0	0	0	0	0	0	0
7-8	0	0	0	1	1	0	0	0	0	0	0	2
6-7	0	0	1	2	1	1	0	0	0	0	0	5
5-6	0	1	2	5	3	2	0	0	0	0	0	14
4-5	0	2	8	12	9	5	2	0	0	0	0	38
3-4	1	7	23	30	21	10	4	1	0	0	0	97
2-3	2	24	66	70	41	16	5	1	0	0	0	225
1-2	9	74	136	99	41	12	3	0	0	0	0	373
0-1	34	94	79	30	7	1	0	0	0	0	0	245
	< 4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	> 13	Tz (s)

Figure 4.4: Average yearly wave scatter diagram for ship type C

encountered most often by type A and least often by type B and wave heights between 1 and 5 m are encountered most often by type B and least often by type A.

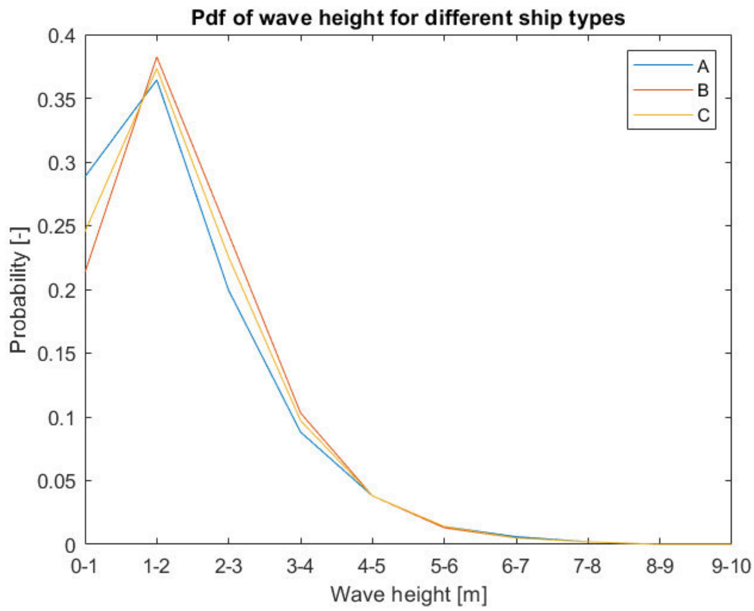


Figure 4.5: Pdf of wave height for different ship types

Secondly, the yearly sailed miles are positively correlated to the encountered waves. This will lead to more power fluctuation cycles. In turn this introduces more harmful emissions and battery degradation. In ascending order most miles are sailed by type A, B and C, as shown in Table 4.2.

Thirdly, the wave period will influence the propulsion plant characteristics. When using an ESS for load levelling in waves the ESS power-over-energy-ratio and wave duration should be of the same order of magnitude in order to improve the propulsion plant layout in terms of weight and volume, which is explained in section 2.5. The wave periods for type B and C are comparable and slightly higher than those of type A. This difference is neither beneficial nor detrimental. When implementing a supercapacitor into the propulsion plant the power-over-energy-ratio should be matched to this wave period. However, the small difference in required power-over-energy-ratio for levelling the waves encountered by type A, B and C can be neglected compared to the C-rate of the battery packs.

4.3. Selection of ship type and sailing area conditions

Taking into consideration the aforementioned, ship type B will be used in continuation of this research. Ship type A is not considered due to the low occurrence of wave heights exceeding 1 meter. Ship type

C is not considered, since a lot of uncertainty is introduced due to the broad sailing area. Therefore, if a supercapacitor is not beneficial in type B, it is assumed that a supercapacitor will also not be beneficial for ship types A and C.

4.4. Time factor determination

By assigning time factors to the loads (time traces) provided by MARIN a load case can be determined that resembles the conditions that ship type B encounters. Figure 4.6 shows the test conditions marked in the type B scatter diagram. Based on the wave density surrounding these test numbers, the time factors can be assigned. However, from a mathematical point of view the time factor for each test should be zero, since a point does not contain any area in the wave scatter diagram.

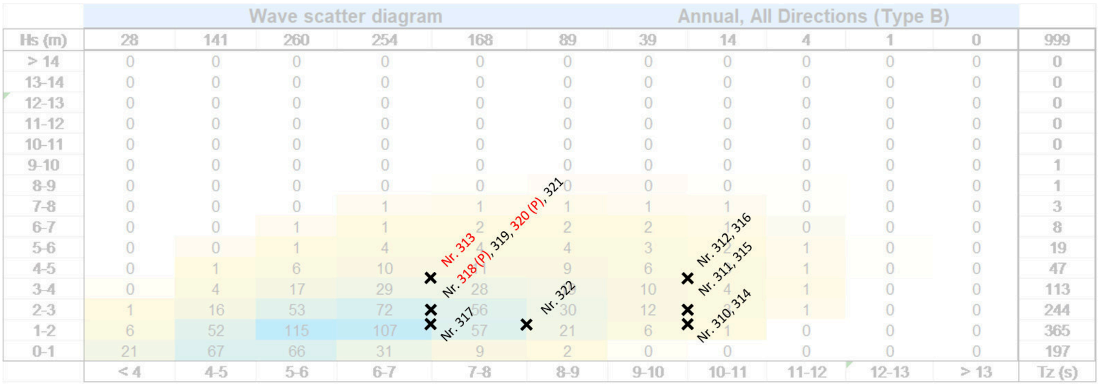


Figure 4.6: Type B scatter diagram including corresponding test conditions

In order to get an approximation of the time factors, several assumptions are made:

- Waves occurring in a certain H and T range are uniformly distributed.
- If multiple test cases correspond to a certain H and T, then it is assumed that each test case occurs just as often.
- The wave scatter diagrams and wave spectra that a yacht will encounter when sailing are identical.
- The cases in which passive stabilizer fins are engaged are disregarded, since these are no realistic operational configuration.
- The H and T input used by MARIN will be assumed to have a range of 1. Overlap between these cases will be disregarded.

In Table 4.3 the amount of waves corresponding to the test conditions (according to the assumptions stated above) is shown, when 999 waves of type B are encountered. The time factors based on these occurrences are shown in Table 4.4. The implementation of these time factors in the simulations can be interpreted as the vessel sailing time in certain conditions. E.g. a vessel of type B will be encountering waves comparable to those in test nr. 316 and 317 for 0.6% and 40.2% of the time. The relative battery degradation in test nr. 316, compared to test nr. 317, can be higher. However, the absolute battery degradation might be less due to the low probability of test nr. 316. This method takes into account the probability of certain environmental conditions in order to acquire realistic final results.

	T [s]		
H [m]	6.5-7.5	7.5-8.5	9.5-10.5
3.5-4.5	n/a	n/a	2
2-3	64	n/a	3
1.25-2.25	66	27	2

Table 4.3: Wave occurrences in 999 waves of type B

Test nr.	Time factor
310	0.009
311	0.013
312	0.009
313	n/a
314	0.009
315	0.013
316	0.009
317	0.386
318	n/a
319	0.187
320	n/a
321	0.187
322	0.180

Table 4.4: Time factors for tests

5

Energy storage system sizing

Sizing of the battery and supercapacitor bank will be based on the propulsive power during the sea-keeping tests. This chapter will discuss the data analysis and how the results were used to determine the ESS size.

5.1. Analsyis of the power consumption in waves

In order to gain insight into the power fluctations the data time traces have been analysed. The main characteristics researched were the amount of energy that needs to be supplied or stored in order to level the loads and the power fluctuation durations.

5.1.1. Wave induced energy shortage and surplus

For this analysis each time trace has been complemented with its average value, as shown in the first graph in Figure 5.1. The average value will serve as reference point for the load levelling. The intersections between the average value and the actual time trace therefore serve as points where a through becomes a crest or vice versa.

Subsequently, each trough and crest is isolated and integrated over time. The values acquired correspond to the amount of energy that should be supplied or stored by the energy storage system (battery and supercapacitor) to level the load to the average power demand. Next, all absolute energy values for the throughs and crests are sorted in ascending order. This series can be plotted into a cumulative distribution function. As shown in the second graph in Figure 5.1, this function shows which part of the fluctuations can be levelled for a certain supercapacitor capacity. E.g. with a capacity of 0.227 kWh 70% of the fluctuations can be levelled. In this figure the required capacities for levelling 50%, 70% and 90% of the fluctuation are shown. Note that it is not accounted for whether this fluctuation requires charging or discharging.

Finally, as shown in the third graph in Figure 5.1, the shaft power variation is integrated over time for the complete test duration. The difference between the lowest and highest value gives insight into the potential accumulated power consumption. By definition the average power demand must create an equally big energy shortage and surplus. Globally this will be the case with the power time traces. However, the local average might not be equal to the global average which means the shortage or suplus is accumulating to a non-zero value. This means the energy storage system needs to (dis)charge for multiple wave periods (t = [180:880]), which increases the capacity required compared to the value based on the cumulative distribution function. However, this problem only occurs when power delivered by the prime mover is constant. When prime mover power output is adjusted, this phenomena will be less noticeable or not present at all. More on the power delivered by the prime mover can be found in section 6.2.

Appendix B can be consulted for an overview of the remaining time traces.

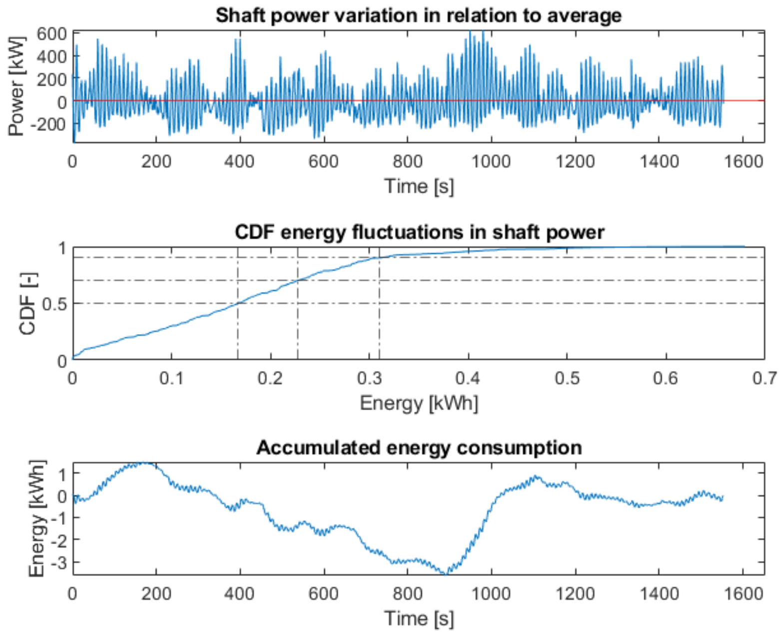


Figure 5.1: 1. Power time trace; 2. Cumulative distribution function; 3. Accumulated power consumption

5.1.2. Power fluctuation duration

Table 5.1 shows the average crest and trough duration for each test and the corresponding weight factors. The bottom row shows a duration of 5.21 s, which is the weighted average crest and trough duration. In order to level this load a supercapacitor with a power-over-energy-ratio of 691 is required. This value must be considered when picking a supercapacitor for use in the simulation.

Test nr.	T [s]	T.f.
310	2.41	0.009
311	2.57	0.013
312	3.26	0.009
314	2.26	0.009
315	2.82	0.013
316	3.16	0.009
317	5.91	0.386
319	5.79	0.187
321	4.81	0.187
322	4.30	0.180
Total	5.21	1.000

Table 5.1: Average crest and trough duration for tests

5.1.3. Analsyis of the power consumption in waves: results

Table 5.2 shows the capacity that a supercapacitor should have in order to level the smallest 50%, 70% or 90% of the power fluctuations, according to subsection 5.1.1. The last row shows the weighted average of all cases. Standing out is the accumulated energy consumption, which is 14 times higher for the weighted average case than required for levelling 90% of the fluctuations. Note that this value is highly influenced by prime mover power output, which is currently assumed as constant. Due to unwanted system behaviour, which will be described in section 6.2, this will not be the case in the model. In the model the prime mover power supply will be adjusted, based on the power demand which is currently also done in Feadships. This will be a long term process (multiple fluctuation periods), since short term ramping should be prevented, but it will reduce the accumulated energy consumption.

Test nr.	50% [kWh]	70% [kWh]	90% [kWh]	Accumulated E [kWh]
310	0.064	0.105	0.152	1.726
311	0.066	0.106	0.154	1.798
312	0.132	0.200	0.311	5.347
314	0.034	0.065	0.109	2.351
315	0.031	0.064	0.123	5.729
316	0.082	0.134	0.221	9.822
317	0.073	0.262	0.515	6.958
319	0.159	0.230	0.333	5.104
321	0.167	0.227	0.310	5.122
322	0.155	0.208	0.269	1.885
Total	0.121	0.231	0.378	5.208

Table 5.2: Required SC capacity for levelling 50%, 70%, 90% and the accumulated energy consumption

5.2. Supercapacitor selection

As described in subsection 5.1.2 a C-rate of 691 is required. This value will determine the type (or brand) of supercapacitor and Table 5.2 will determine the size (or amount) of supercapacitors. Table 5.5 shows multiple supercapacitors that are currently on the market for transport purposes. In terms of C-rate, Maxwell and Capcomp produce fitting supercapacitors. However, Maxwell achieved an 18% higher energy density at the cost of a 2% lower power density. Therefore the 160V – BMOD0006 E160 C02 [16] will be used in continuation of this research. This supercapacitor is specifically designed for application in wind turbine pitch control, but also suitable for small UPS systems, industrial applications and heavy duty machinery.

Fabricator	Power density [W/kg]	Energy density [Wh/kg]	C-rate [-]
ioxus [17]	755	2.9	260
Maxwell [16]	2500	4.0	625
Capcomp [18]	2560	3.4	752
Skeleton [19]	8520	4.1	2078

Table 5.3: Supercapacitor specifications which are currently available on the market

In Table 5.4 the specifications of 160V – BMOD0006 E160 C02 are shown.

Voltage	160 V
Maximum string voltage	750 V
Current	12 A
Peak current	170 A
Energy capacity	20.6 Wh
Power	12.75 kW
Mass	5.1 kg
Volume	6.8 L
Cooling	Natural convection

Table 5.4: 160V BMOD0006 E160 C02 specifications

5.3. Propulsion plant configurations

Most battery packs in present day Feadships are dimensioned based on their power output. Therefore, they can store more energy than is usually required. This will be considered when setting up the propulsion plant configurations. In this research one side of the drive train will be considered.

Generator power	4250 kW
B capacity	500 kWh
C-rate B	0.7
Round trip efficiency B	0.95
SC capacity	0-0.32 kWh (0 in reference case)
C-rate SC	625
Round trip efficiency SC	0.95
Efficiency converter subsection 5.3.3	0.98

Table 5.5: Supercapacitor specifications which are currently available on the market

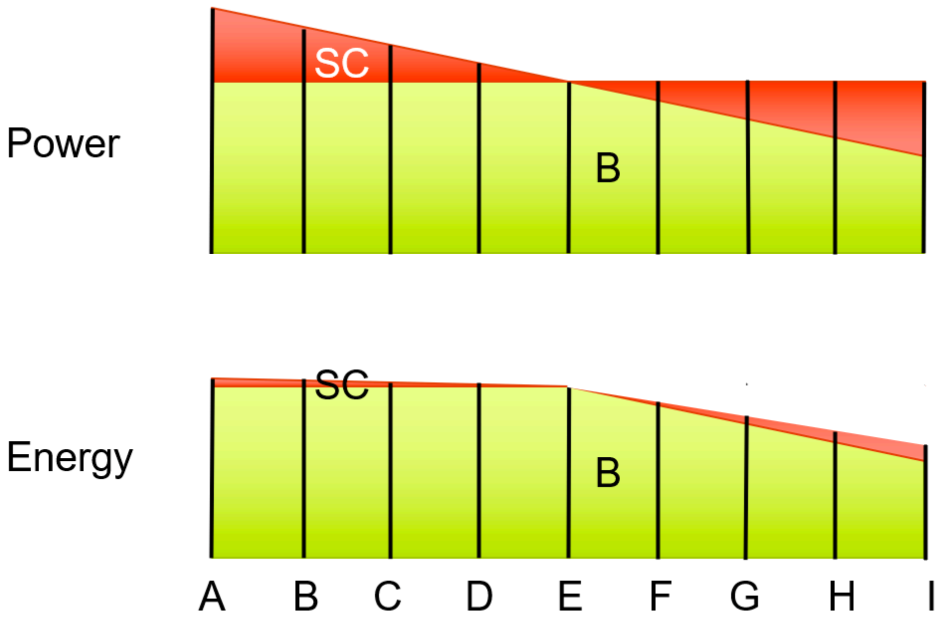


Figure 5.2: Conceptual overview of configuation A-I (Batteries in green; Supercapacitors in red)

5.3.1. Qualitative set-up

In order to guarantee enough power output by the combined ESS, the power will be kept constant when adding supercapacitors, as illustrated in Figure 5.4 (case F-I). The specific characteristics are shown in Table 5.6 and Figure 5.4. Case E will serve as reference case, where no supercapacitors are available. Additonally, albeit counter-intuitive, cases A-D are added. In these cases the battery capacity is kept constant and supercapacitor banks are added. This introduces a slight increase in total energy capacity and a significant increase in power output of the combined ESS. These plant configurations are added since the introduction of supercapacitors introduces some disadvantages with regards prime mover power output. For additional explanations subsection 7.1.2 and subsection 7.2.2 can be consulted.

5.3.2. Quantitative set-up

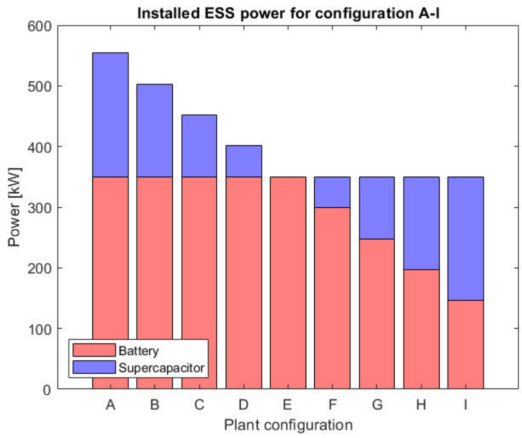
According to subsection 5.1.3 the supercapacitor should have a capacity of respectively 0.121, 0.231 and 0.378 kWh in order to level 50%, 70% and 90% of fluctuations for the weighted average case. Based on these specifications, configurations A-H are determined. These are further explained in Figure 5.3 and Table 5.6.

5.3.3. Supercapacitor bank layout

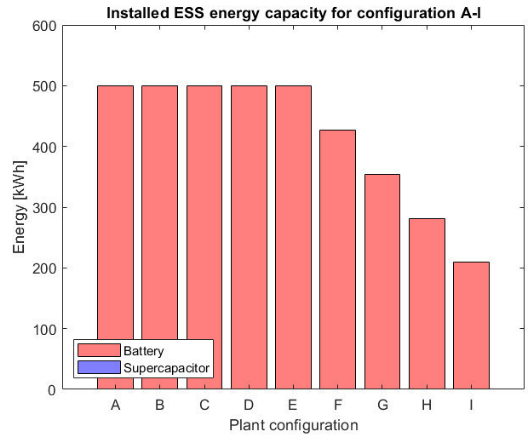
A DC-board is used to connect the energy storage systems, the prime mover and the propeller. Based upon previous Feadships a DC voltage of 1000V is assumed. For discharging, the voltage of the energy storage systems should exceed the grid voltage. For charging the voltage should subceed the grid voltage. When one energy storage system is connected to this grid this can be done in a passive way, which means no voltage regulation is required. However, when installing a second energy storage

	A	B	C	D	E	F	G	H	I
P_B[kW]	350	350	350	350	350	299	248	197	146
P_{SC}[kW]	204	153	102	51	0	51	102	153	204
E_B[kWh]	500	500	500	500	500	427	354	281	209
E_{SC}[kWh]	0.33	0.24	0.16	0.08	0.00	0.08	0.16	0.24	0.33
m_B[kg]	4545	4545	4545	4545	4545	3883	3220	2558	1896
m_{SC}[kg]	82	61	41	20	0	20	41	61	82
V_B[L]	3846	3846	3846	3846	3846	3286	2725	2165	1604
V_{SC}[L]	108	81	54	27	0	27	54	81	108
P_{tot}[kW]	554	503	452	401	350	350	350	350	350
E_{tot}[kWh]	500	500	500	500	500	427	354	282	209
m_{tot}[kg]	4627	4606	4586	4565	4545	3903	3261	2619	1978
V_{tot}[L]	3954	3927	3900	3873	3846	3313	2779	2246	1713

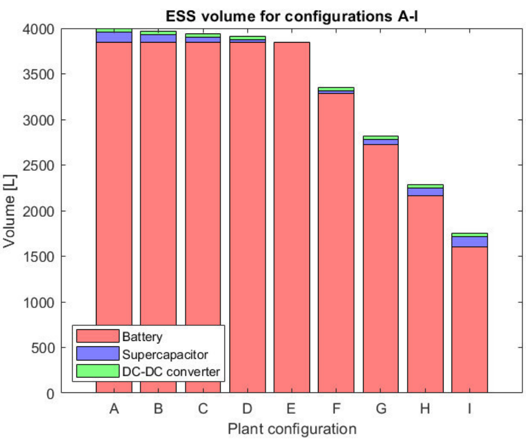
Table 5.6: Propulsion plant configurations A-E



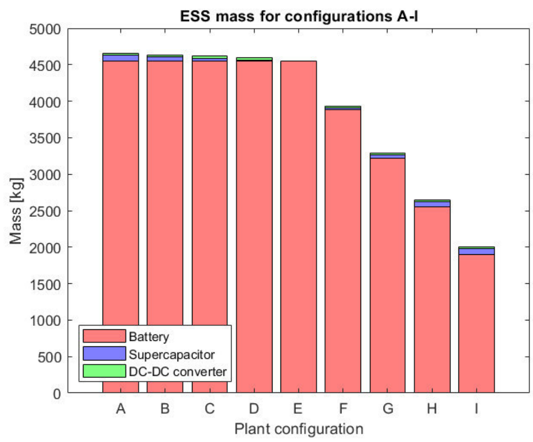
(a) Combined installed ESS power



(b) Combined installed ESS energy capacity



(c) Combined ESS volume



(d) Combined ESS mass

Figure 5.3: The installed power, energy capacity, volume and mass of the combined energy storage system for configurations A-I

system the voltage should be regulated by means of a DC-DC converter in order to control power supply between the multiple systems. For the DC-DC converter to function properly the voltage of the energy storage system should always be lower than the grid voltage [20].

This imposes a limit of 6 supercapacitors connected in series in the supercapcitor bank. If more supercapacitors would be connected in series the resulting voltage would exceed the grid voltage. However, according to the Maxwell the maximum string voltage for this supercapacitor is 750 V, which

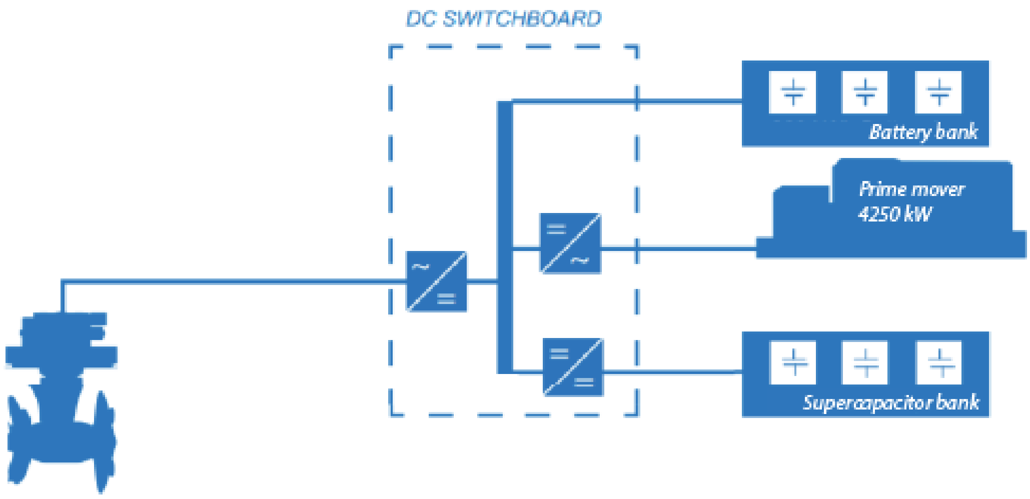


Figure 5.4: Schematic overview of the propulsion plant set up

equals 4 supercapacitor modules in series [16]. This means the supercapacitor bank will feature a maximum of 4 supercapacitors in series. In order to increase the capacity to the required level sets of 4 supercapacitors in series will be added in the bank in parallel. The bank supercapcitor bank layouts for each configuration are:

- Configuration A: 4S4P (4 parallel strings; a string contains 4 supercapacitor in series)
- Configuration B: 4S3P
- Configuration C: 4S2P
- Configuration D: 4S1P
- Configuration E: no supercapacitors
- Configuration F: 4S1P
- Configuration G: 4S2P
- Configuration H: 4S3P
- Configuration I: 4S4P

The DC-DC converter that will be used is the RedPrime DC-DC Converter 200 kW, 1200V [20]. The operational characteristics are shown in Table 5.7. An advantage of this converter is the minimum low-voltage side voltage of 10. The converter therefore allows an ESS voltage range of 10 to 640 V, which means an SoC of 2% till 100% is allowed. Below 2% SoC the ESS voltage will subceed 10 V, which will not be allowed.

Nominal power	200 kW
Minimum low-voltage side voltage	10 V
Maximum low-voltage side voltage	1150 V
Maximum low-voltage side current	250 A
Minimum high-voltage side voltage	60 V
Maximum high-voltage side voltage	1200 V
Maximum high-voltage side current	200 A
Efficiency	98%
Mass	30 kg
Volume	41 L
Cooling	Forced air - internal fans

Table 5.7: RedPrime DC-DC Converter 200 kW, 1200V [20]

6
Propulsion plant model

In order to get insight into the added value of supercapacitor energy storage not only the static operation, but also the dynamic operation of this system must be considered. A propulsion model is built for this in Matlab. This chapter will discuss which components are included, what the control strategy is and which data is included in the output.

6.1. Model components

The required complexity of the propulsion model highly influences which model components should be included. If power management is the goal, then the electrical grids, power electronics and energy storage and supply units should be modelled with the corresponding electrical parameters. If energy management is the goal, then modelling of the energy sources, sinks and storages suffices. With the correct rule-based control the system behaviour can be included. This prevents the need to model all physical system components, which greatly reduces the system complexity. The model set-up which is used for this research is shown in Figure 6.1. The components included are a prime mover, a battery pack, a supercapacitor pack and the electric motor driving the propeller. For the prime mover, the battery and the supercapacitor the minimum and maximum power are included in the model. The maximum ramp speed of these components is considered, but not included in the model since they exceed the maximum rate of change in the power consumption. For the supercapacitor and the battery the minimum and maximum energy capacity and the round trip efficiency are included.

The prime mover can charge the battery and supercapacitor or directly power the electric motor. The battery and supercapacitor can power the electric motor by discharging.

6.2. Energy management

The energy management strategy selected for this research is rule based control. Rule based control is selected because of its simplicity and because it is deemed suitable for making a first evaluation of supercapacitor energy storage in a yacht propulsion plant. For further considerations with regards to energy management section 9.4 can be consulted. The rule based control is implemented in the model by means of three rules. These rules are discussed in section subsection 6.2.1 till subsection 6.2.3.

6.2.1. Rule 1: Component hierarchy

The main goal of this research is to aim for more continuous loading of the prime mover. A secondary goal is deloading the batteries by transferring load to the supercapacitor. These goals are introduced by a (negative) supply hierarchy. When a power difference between the demand and supply side is introduced, the supercapacitor is addressed. If the supercapacitor cannot provide in this, the batteries are addressed. If the batteries cannot provide in this, the generator power ouput is adjusted. This rule adjusts generator power only as a last resort.

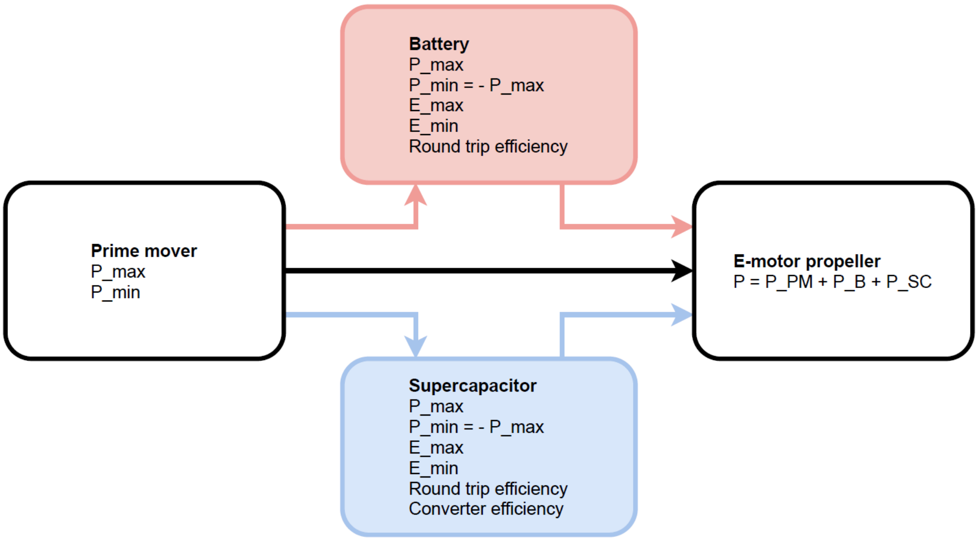


Figure 6.1: System components and corresponding parameters

6.2.2. Rule 2: Supercapacitor over(dis)charge protection

The first rule can be used to provide in the required power. However, once the battery or supercapacitor reaches an SoC of 0% or 100% the system behaves unstable. As support for the following two examples, see Figure 6.2. E.g. suppose a fluctuating propulsion power of 3000 kW and 2700 kW is provided by the prime mover. The remaining 300 kW and power fluctuations are supplied by discharge of the supercapacitor. Once the supercapacitor is fully discharged, the power potential drops to zero and the power shortage of 300 kW is transferred to the prime mover. This is a sudden load step for the prime mover, which is undesirable.

The supercapacitor over(dis)charge protection rule can prevent this. Once the supercapacitor drops below a certain SoC a negative feedback loop will be triggered. This loop will lessen the effects of the process described above by gradually adjusting generator power in advance. It is still possible to discharge the supercapacitor completely, but if this is the case the supercapacitor is no longer supplying 300 kW and therefore the load transfer to the generator will be smaller. E.g. suppose a fluctuating propulsion power of 3000 kW and 2700 kW is provided by the prime mover. The remaining 300 kW and power fluctuations are supplied by discharge of the supercapacitor. Once the supercapacitor drops below 15% SoC the feedback loop transfers load to the prime mover. Either the supercapacitor does not discharge completely due to the load transfer or the supercapacitor is completely discharged when it was only supplying a value of less than 300 kW. The difference should be supplied by the generator. This is a sudden but smaller load step compared to the first case. The same logic is applied to the upper value of the SoC.

A comparable strategy is used in charging and discharging of current battery packs in feadships. The goal is to prevent extreme values in SoC of the batteries, in order to limit degradation. Although the goal might be different, the approach is similar. The rule is implemented by means of Equation 6.1. For overdischarge protection Equation 6.2 is used.

$$P_{DG}(i+1) = P_{DG}(i) + x \cdot \frac{SoC_{min} - SoC(i)}{SoC_{min}} \cdot P_{SC,max} \tag{6.1}$$

$$P_{DG}(i+1) = P_{DG}(i) + x \cdot \frac{SoC(i) - SoC_{max}}{1 - SoC_{max}} \cdot P_{SC,max} \tag{6.2}$$

In order to maximize potential of this rule the x-coefficient can be adjusted. This should be done for each combination of the power demand, the minimum and maximum target SoC (SOC_{min} and SOC_{min}), the supercapacitor power output ($P_{SC,max}$) and coefficient y. The latter will be explained in subsection 6.2.3. This rule will often interfere for one or few wave periods and the behaviour is highly influenced by the local power demand.

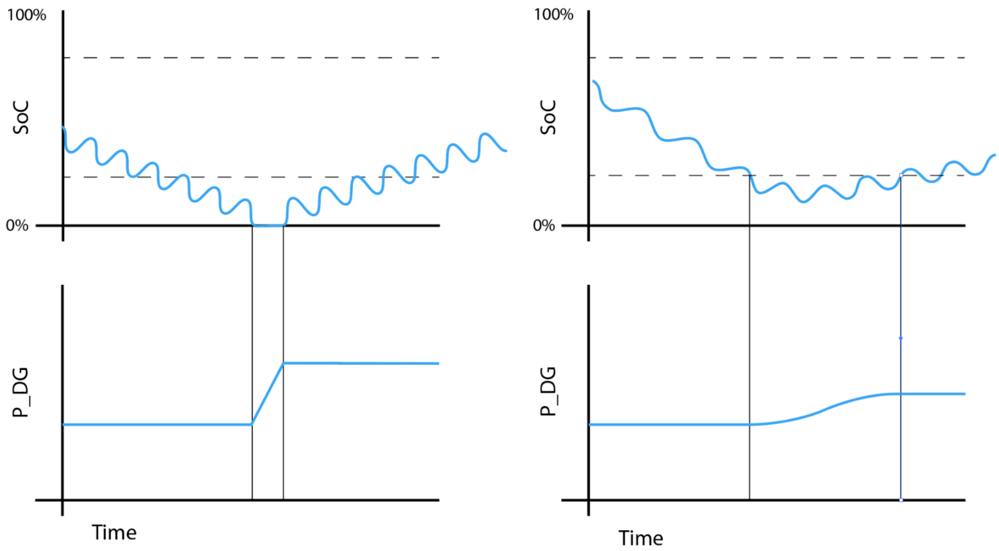


Figure 6.2: Prime mover power output with and without supercapacitor overdischarge protection

6.2.3. Rule 3: Generator power adjustment

Preferably, the supercapacitor is used to level load flucatuations with a period of around 5.8 seconds. However, accumulating load fluctuations can also occur which have longer durations. During these fluctuations the supercapacitor will quickly be completely charged or discharged and therefore no longer level loads. An example of this is given in Figure 6.3 around t = 600s. This corresponds to a steep slope in the graph of the accumulated energy consumption. In these cases, where power demand deviates from the average power demand for multiple fluctuations, it is beneficial to adjust the generator power. This lowers the difference between power demand and generator power, therefore demanding less accumulated power from the supercapacitor, which gives more potential for load levelling.

This rule is implemented by taking the moving average. Part of the difference between this moving averge and generator power will be added to the generator power. This is implemented by means of Equation 6.3. Both the over(dis)charge protection and the generator power adjustment rule have a similar effect on the system behaviour. However, the first rule applies as a back-up when the supercapacitor SoC approaches extreme values.

$$P_{DG}(i+1) = P_{DG}(i) + y \cdot (movmean(P) - P_{DG}(i)) \tag{6.3}$$

In order to maximize potential of this rule the y-coefficient can be adjusted. This should be done for the number of elements in the moving average and the supercapacitor power output ($P_{SC,max}$). This rule will interfere continuously and the behaviour is hardly influenced by local power demand.

6.2.4. Sensitivity analysis

The over(dis)charge protection rule requires specific tuning, due to its dependence on local events where the SoC ex- or subceeds predetermined levels. Besides, it depends on more variables than the generator power adjustment rule. Due to new insights during the simulations, this rule even turns out to have a counterproductive effect when it is not sufficiently tuned. It is not feasible to include this process in the current research. Therefore, this rule will not be used in the simulations. More on the counterproductive effect of this rule will be discussed in section 7.3. More on how this rule might be implemented in the future is discussed in chapter 9.

For the implementation of the generator power adjustment rule a sensitivity analysis is performed. For this analysis test nr. 317 is selected since this corresponds to the most frequently occurring environmental condition. For this power demand, multiple moving averages with varying dataset sizes have been set up. These are shown in Figure 6.4. The moving average should as little as possible be influenced by specific waves, but should be able to follow the center line of the signal. Based on test nr. 317 an 8000 element moving average is selected. This corresponds to a 152 second moving average period.

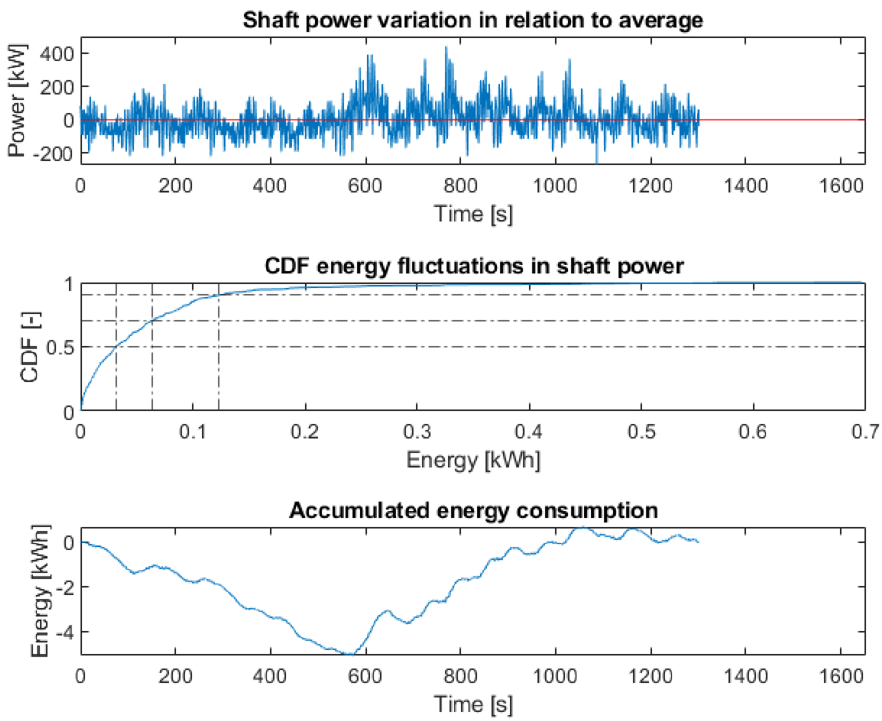


Figure 6.3: Shaft power, CDF and accumulated power data for test nr. 315

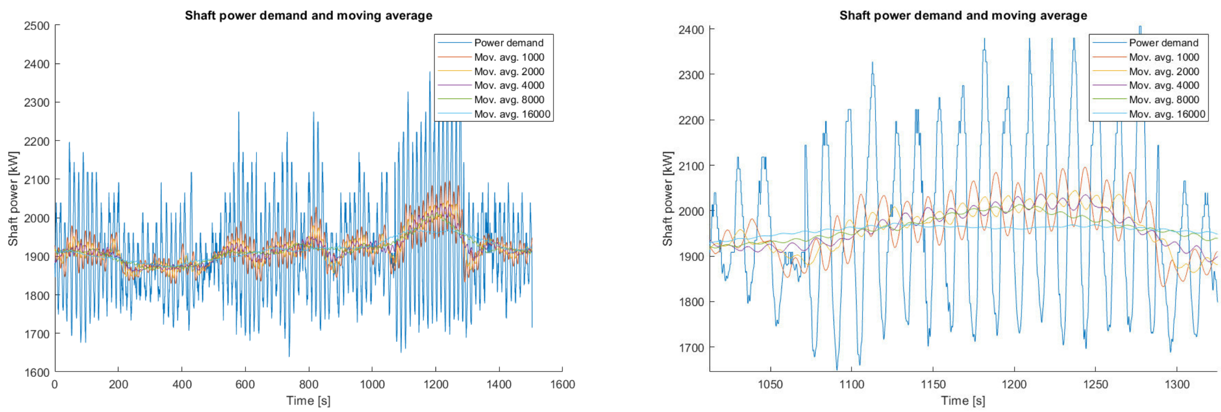


Figure 6.4: Power demand nr. 317 and moving averages

Next, for each plant configuration case nr. 317 is simulated, for multiple y-coefficients, which are implemented in Equation 6.3. For each y-coefficient, the P_SC/P_B and the average prime mover ramp rate are exported. For each plant configuration the y-coefficient corresponding to the highest value of P_SC/P_B is selected. Some local extremes were present in the P_SC/P_B, which resulted in cases where a marginally lower P_SC/P_B corresponded to a much lower ramp rate. If one is optimizing for ramp rate this trade-off can be made. However, this is not done in this research in order to not give a value judgement about plant behaviour. Configuration E is an an exception to this, where P_SC/P_B is by definition zero. In this case a y-coefficient of 0.0005 is selected, since a 3% raise in battery use contributed to a 60% drop in ramp rate compared to a y-coefficient of 0. The y-coefficients selected for each plant are shown in Table 6.1. For the complete output Appendix C can be consulted.

Plant configuration	Case 1	Case 2
A	0.0010	0.0015
B	0.0015	0.0020
C	0.0010	0.0015
D	0.0010	0.0015
E	0.0005	0.0005
F	0.0015	0.0025
G	0.0030	0.0100
H	0.0025	0.0045
I	0.0030	0.0010

Table 6.1: y-coefficients for case 1 and 2

6.3. Model output

When running the simulations the Matlab script generates the output shown in Table 6.2, for each different power demand. The output that is used in chapter 7 consists of the weighted average for the combined environmental condition of the last five outputs. All figures and results that will be shown in chapter 7 are acquired set up by using one of the outputs below.

Symbol	Unit	Explanation
$P_{dg}(t)$	$[kW]$	Prime mover power output
$P_{del}(t)$	$[kW]$	Delivered power by propulsion plant
$P_{SC}(t)$	$[kW]$	Supercapacitor power supply
$P_B(t)$	$[kW]$	Battery power supply
$E_{SC}(t)$	$[kWh]$	Energy stored in supercapacitor
$E_B(t)$	$[kWh]$	Energy stored in battery
$E_{SCfinal}$	$[kWh/h = kW]$	Total supercapacitor energy throughput per hour
E_{Bfinal}	$[kWh/h = kW]$	Total battery energy throughput per hour
$cycles_{SC}$	$[/h]$	Total supercapacitor cycles per hour
$cycles_B$	$[/h]$	Total battery cycles per hour
$avgramp$	$[kW/s]$	Average ramp rate of the prime mover

Table 6.2: Model output that is used for analysing plant behaviour

7 Results

In chapter 5 the added power (A-D) and constant power (F-I) configurations are introduced. The former features more installed power at the cost of a slight increase in ESS weight and volume. The latter features a significant ESS weight and volume reduction, while maintaining the reference power output. However, an increase in ESS power output does not guarantee improved performance and constant ESS power output does not guarantee similar performance. This chapter will present and explain the results of the power plant simulations. The effect of supercapacitor energy storage on battery use will be discussed for supercapacitors with varying power-over-energy-ratios. Also the effect on the prime mover behaviour will be discussed.

7.1. Simulation results: Case 1, C-rate = 625

In Table 7.1 the average power demand and hourly cycles performed by the supercapacitor and battery bank are shown. The second last column shows the average ramping rate by the prime mover. The last column gives the ratio between the delivered power by the supercapacitors and the batteries.

	P_{SC} $[kW]$	$cycles_{SC}$ $[/h]$	P_B $[kW]$	$cycles_B$ $[/h]$	$avgramp$ $[kW/s]$	P_{SC}/P_{SC} $[-]$
0	n.a.	n.a.	n.a.	n.a.	78.38	n.a.
A	41.33	63.31	13.58	0.014	0.90	3.04
B	36.05	73.63	19.00	0.019	1.17	1.90
C	28.28	86.64	27.04	0.027	1.36	1.05
D	16.96	103.93	38.52	0.039	1.90	0.44
E	0.00	0.00	56.30	0.056	2.45	n.a.
F	17.07	104.59	38.07	0.045	3.38	0.45
G	28.63	87.70	25.97	0.037	4.84	1.10
H	36.94	75.44	17.32	0.031	6.41	2.13
I	43.53	66.68	10.11	0.024	9.52	4.31

Table 7.1: Simulation output: Case 1 (C-rate = 625)

Figure 7.1, Figure 7.2 and Figure 7.3 give more insight into the operational characteristics during test nr. 317. These figures concern configuration A, E and I. The first graph shows the propeller power demand, the second the combined delivered power by the prime mover, supercapacitor and batteries, the third graph the battery power, the fourth graph the supercapacitor power, the fifth graph the SoC of the battery, the sixth graph the SoC of the supercapacitor and the seventh graph the prime mover power output. Note that the prime mover power becomes increasingly less smooth when going from case A to I. This will be elaborated upon in subsection 7.1.2. Additionally, the batteries are more often engaged in configuration E compared to configuration A and I. This will be further explained in subsection 7.1.1.

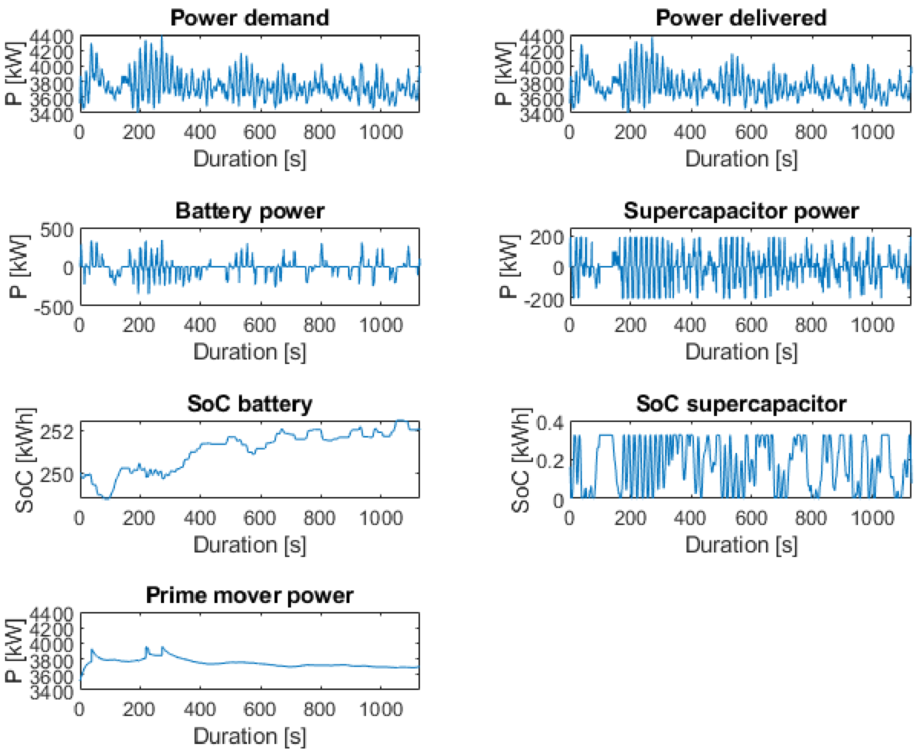


Figure 7.1: Propulsion plant data (configuration A) during execution of test nr. 317

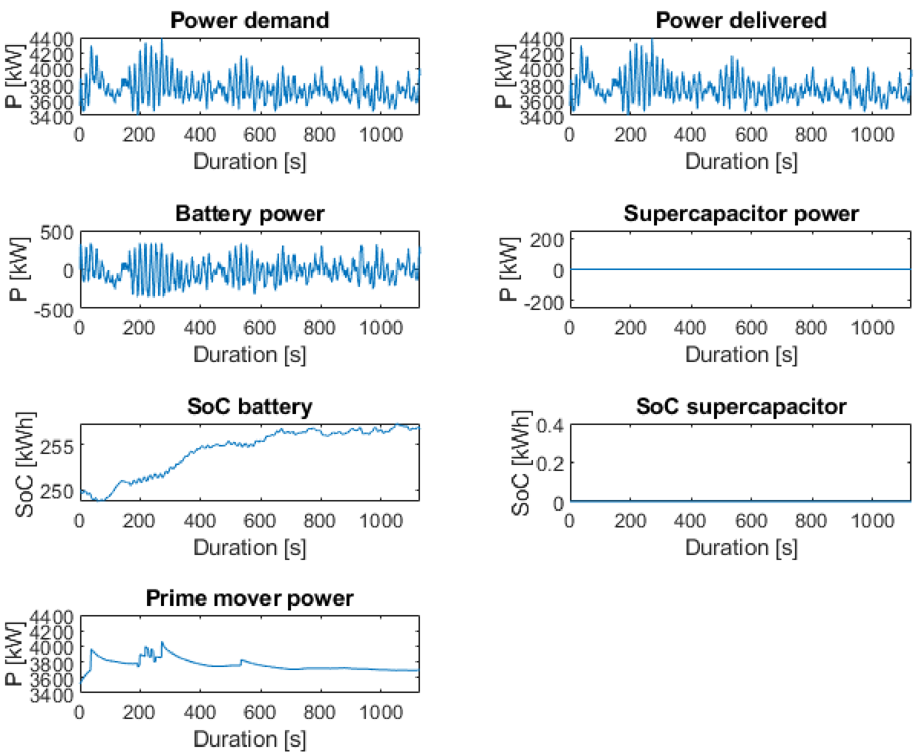


Figure 7.2: Propulsion plant data (configuration E) during execution of test nr. 317

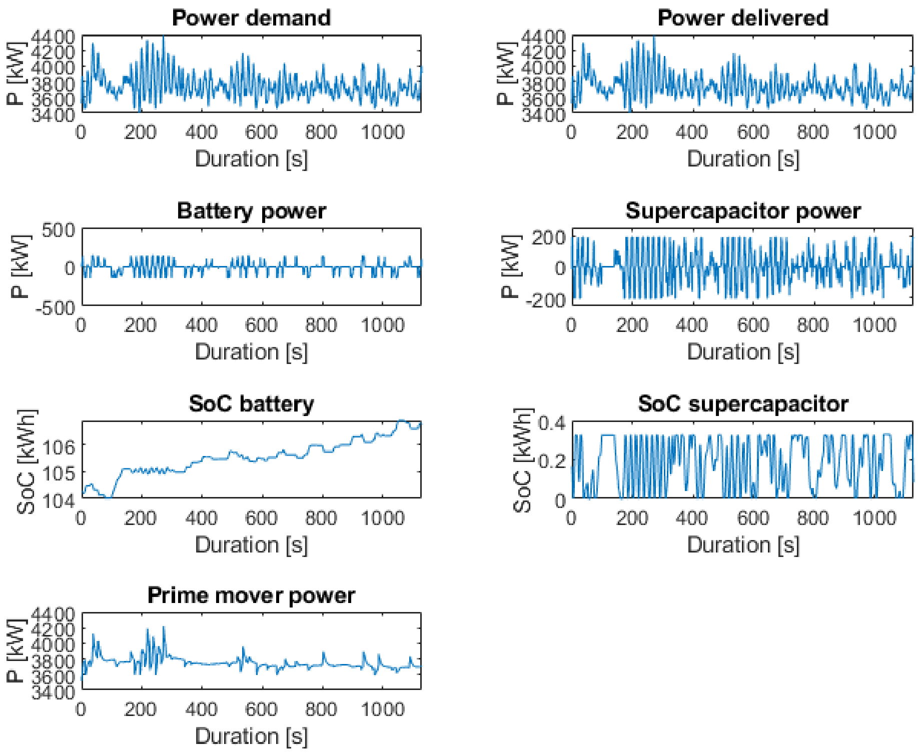


Figure 7.3: Propulsion plant data (configuration I) during execution of test nr. 317

7.1.1. Supercapacitor and battery energy storage and consumption

For supercapacitor energy storage the power output is positively correlated with the energy capacity. This effect is similar for cases A-D and F-I. As can be seen from the supercapacitor cycles, this effect is not proportional. Increasing the energy capacity by factor x, does not lead to a power output increase of factor x. With regards to the supercapacitor operational life it is beneficial to install a bigger bank, since it will execute less cycles per hour.

The same effect holds for the batteries in case F-I. In case E to A the battery power decreases, while the battery capacity remains constant. This effect is caused by the increasing energy capacity and nominal power of the supercapacitor. This enables the supercapacitor to level a bigger part of the fluctuations, which means the batteries less often have to supply power.

If the battery bank will perform less cycles, it is likely that the battery degradation reduces compared to configuration E. However, battery capacity degradation is a non-linear process and depends on more operational characteristics than the average cycles per unit time. Examples are the depth of discharge, mean state of charge, cell temperature and the (dis)charge amperage. section 9.5 will explain how a battery lifetime elongation estimation can be set up [7].

7.1.2. Prime mover ramping behaviour

Configuration 0 serves as reference for the prime mover ramping behaviour. This case shows the average ramping rate is 78.38 kW/s when no energy storage systems are present. The implementation of batteries lowers this value to 2.45 kW/s. Compared to this case the ramp rate decreases when adding additional energy storage and increases when replacing energy storage.

In Figure 7.7 the prime mover power output during test nr. 317 is shown for configuration A, E and I. This is the same data as is shown in Figure 7.1, Figure 7.2 and Figure 7.3. This figure illustrates why the average ramp rate in configuration I increased drastically. Each time the supercapacitor is (de)saturated the load is transferred to the battery pack. However, in case I the battery pack often did not have a sufficient power output, which introduced a load transfer to the prime mover. Therefore, many load steps can be observed in case I compared to A and E.

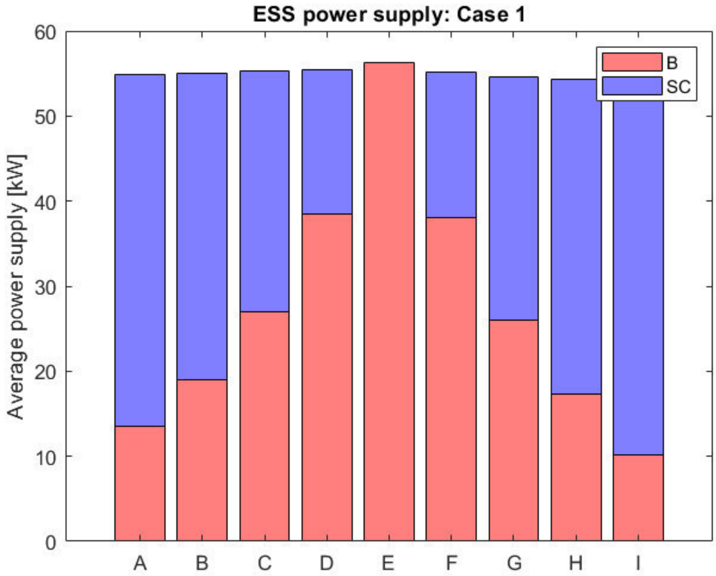


Figure 7.4: Supercapacitor and battery power supply

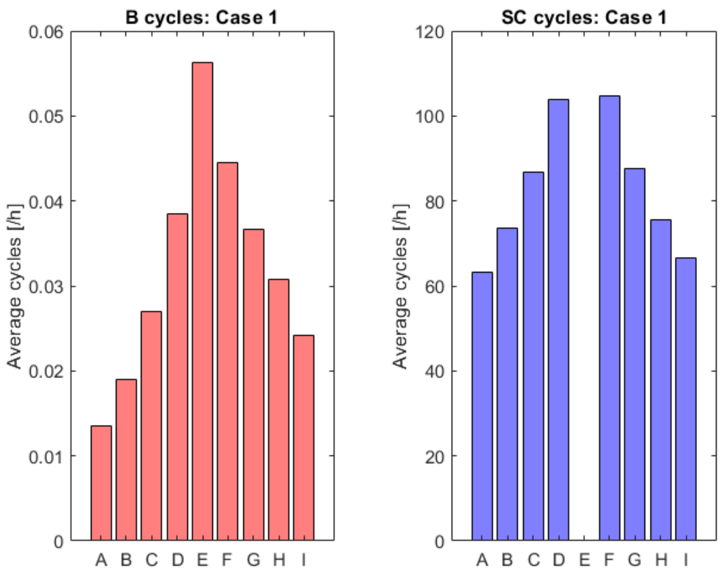


Figure 7.5: Supercapacitor and battery hourly cycles

The ramp rate in case A-D is lower compared to the battery only case because the nominal power output is increased. This means the fluctuations will more often be within the operational range of the ESS and the prime mover is less often required to make a load step. It can be seen that the returns in terms of ramp rate are diminishing when adding even more supercapacitors. This is due to the fact that bigger fluctuations have a lower probability of happening. The average ramp rate magnitude will be dominated by the the ramping which is introduced by the generator power adjustment rule. If the ramp rate is a critical factor in design, adjusting the energy management strategy might offer more benefits than simply adding more supercapacitors.

The ramp rate in case F-I increases drastically. This is caused by supercapacitor (de)saturation. Once this happens, its power supply or storage potential becomes zero and the battery needs to account for this. However, compared to case A-D the battery is smaller. This raises the possibility that

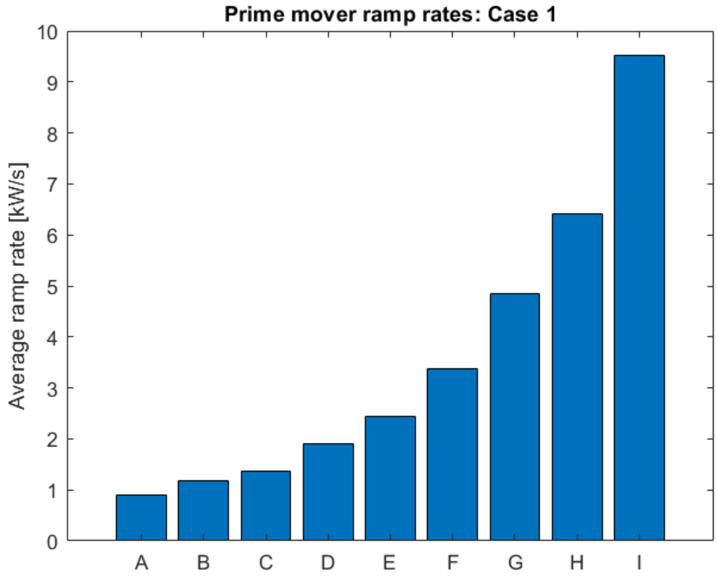


Figure 7.6: Prime mover average ramp rate

the power fluctuation is bigger than the battery nominal power, in which case a power adjustment by the prime mover is required. This effect becomes more evident towards case I, since the ratio between nominal supercapacitor and battery power increases.

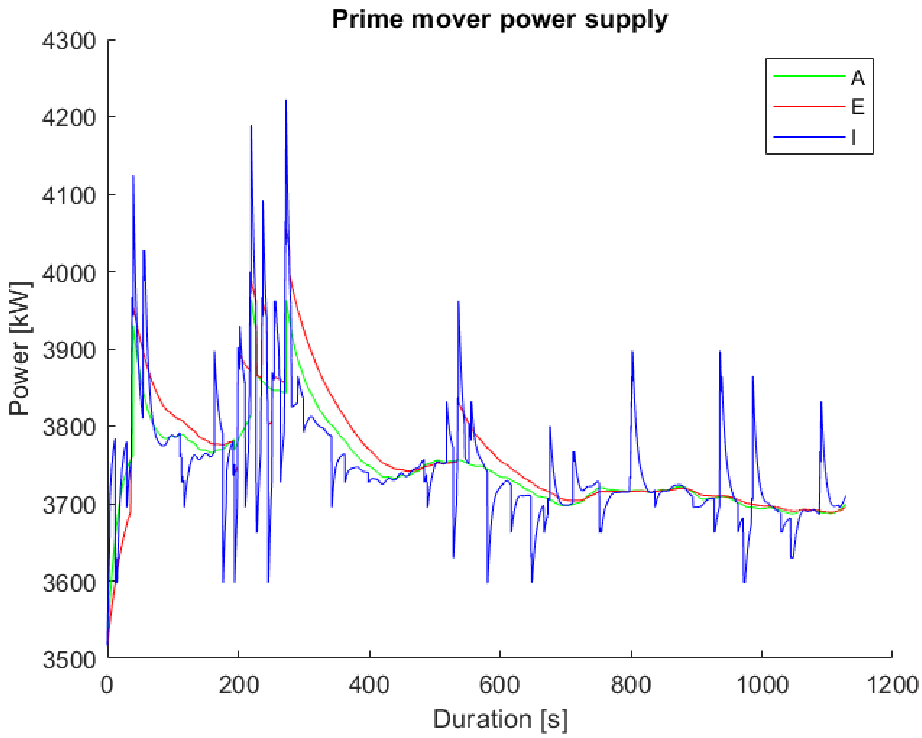


Figure 7.7: Prime mover power output during execution of test nr. 317 for plant configuration A, E and I

7.2. Simulation results: Case 2, C-rate = 200

The results in subsection 7.1.2 are not beneficial if one wants to optimize for plant size (configuration F-I) and low ramp rates. This is due to the fact that the supercapacitor frequently (de)saturates, which causes a gap in energy storage or supply which needs to be absorbed by the prime mover. The supercapacitor energy capacity is a bottleneck in this process. Therefore, another case will be added in which a lower C-rate will be used. This will lead to an increased propulsion plant size compared to case 1, but could be beneficial to prime mover ramping behaviour. The new C-rate is set at 200. Before running of the new simulations the sensitivity analysis is done for a C-rate of 200. This was used to determine new coefficient for the generator power adjustment, which is explained in subsection 6.2.3. In Table 7.2 the simulation results are shown.

	P_{SC} $[kW]$	$cycles_{SC}$ $[/h]$	P_B $[kW]$	$cycles_B$ $[/h]$	$avgramp$ $[kW/s]$	P_{SC}/P_{SC} $[-]$
0	n.a.	n.a.	n.a.	n.a.	78.38	n.a.
A	45.59	22.35	9.40	0.009	0.65	4.85
B	40.69	26.59	14.43	0.014	0.94	2.82
C	32.50	31.86	22.79	0.023	1.19	1.43
D	19.70	38.63	35.62	0.036	1.84	0.55
E	0.00	0.00	56.30	0.056	2.45	0.00
F	19.68	38.59	35.33	0.041	3.39	0.56
G	32.84	32.19	21.46	0.030	5.19	1.53
H	40.85	26.70	13.14	0.023	5.61	3.11
I	46.72	22.90	8.01	0.019	5.04	5.84

Table 7.2: Simulation output: Case 2 (C-rate = 200)

7.2.1. Supercapacitor and battery energy storage and consumption

In Figure 7.8 the ESS power supplies for both cases are compared. The difference between in C-rate does not have an impact on the combined power supply by the ESSs. However, the supercapacitor power increased for every configuration in case 2.

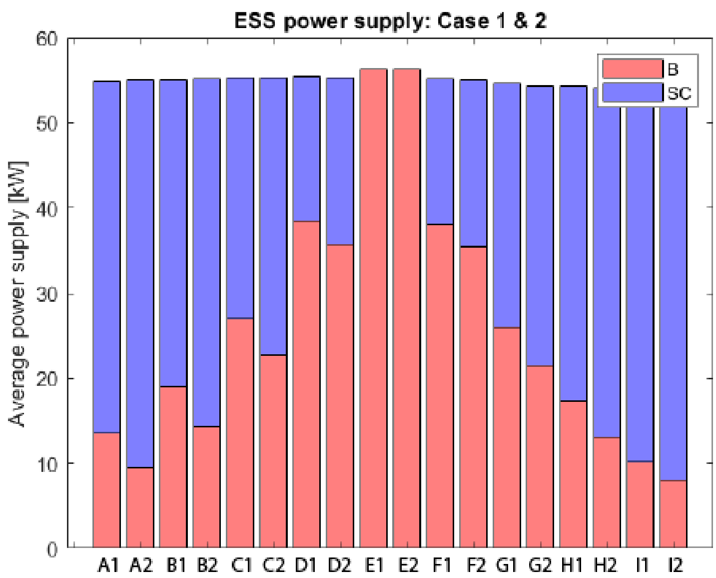


Figure 7.8: Supercapacitor and battery power supply comparison for case 1 and 2

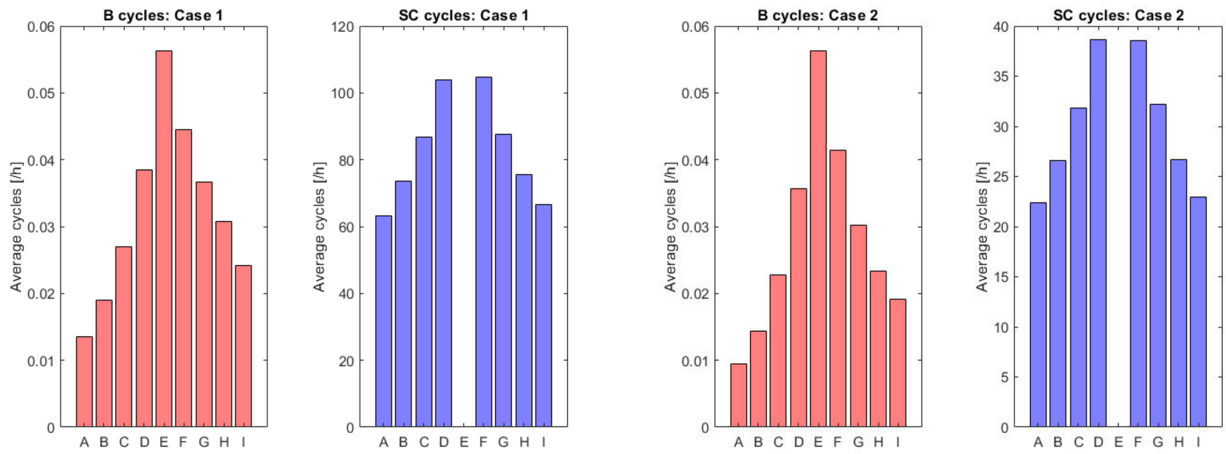


Figure 7.9: Supercapacitor and battery hourly cycles for case 1 & 2

7.2.2. Prime mover ramping behaviour

In Figure 7.10 the prime mover ramp rates for case 1 and 2 are shown. Here it can clearly be seen that increasing the energy capacity of the additional energy storage system lowers the ramp rate of the prime mover. Due to local extremes, which are described in subsection 6.2.3 the ramp rate for configuration I in case 2 has a deviating value compared to the trend among the other configurations.

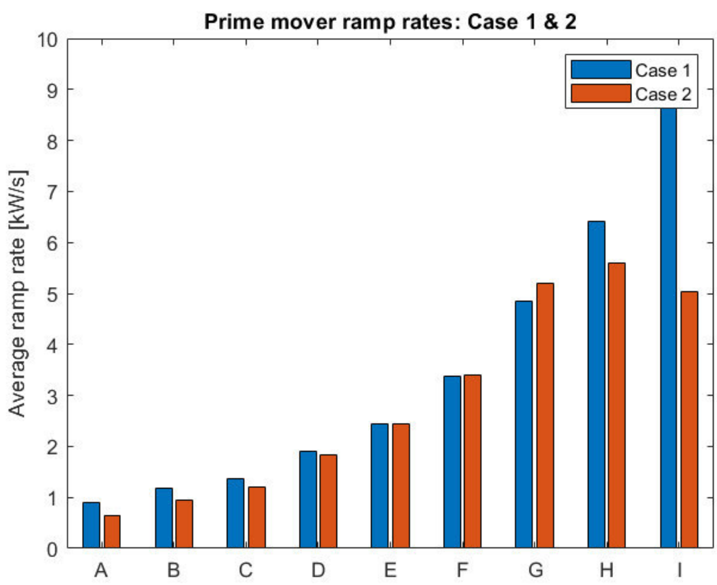


Figure 7.10: Prime mover average ramp rate

7.3. Counterproductivity of Rule 2

During the simulations several inexplicable results where gathered, in which installing additional supercapacitor power lead to more ramping by the prime mover. It was deemed that this could be caused by the unpredictable nature of supercapacitor over(dis)charge protection (Rule 2). After rerunning the simulations without Rule 2 more logical results where obtained. With regards to interfering the prime mover power output, Rule 2 is turbulent of nature. In order to illustrate this, test nr. 317 is rerun with configuration A. This is done once with only Rule 3 engaged and once with Rule 2 and 3 engaged. The operational data for these runs is shown in Figure 7.11 and Figure 7.12. Due to Rule 2 the supercapacitor SoC oscillates at a much higher frequency and, as expected, never (de)satures. This is shown in Figure 7.13. However, this results in steep transient behaviour in the prime mover power output. A comparison is shown in Figure 7.14.

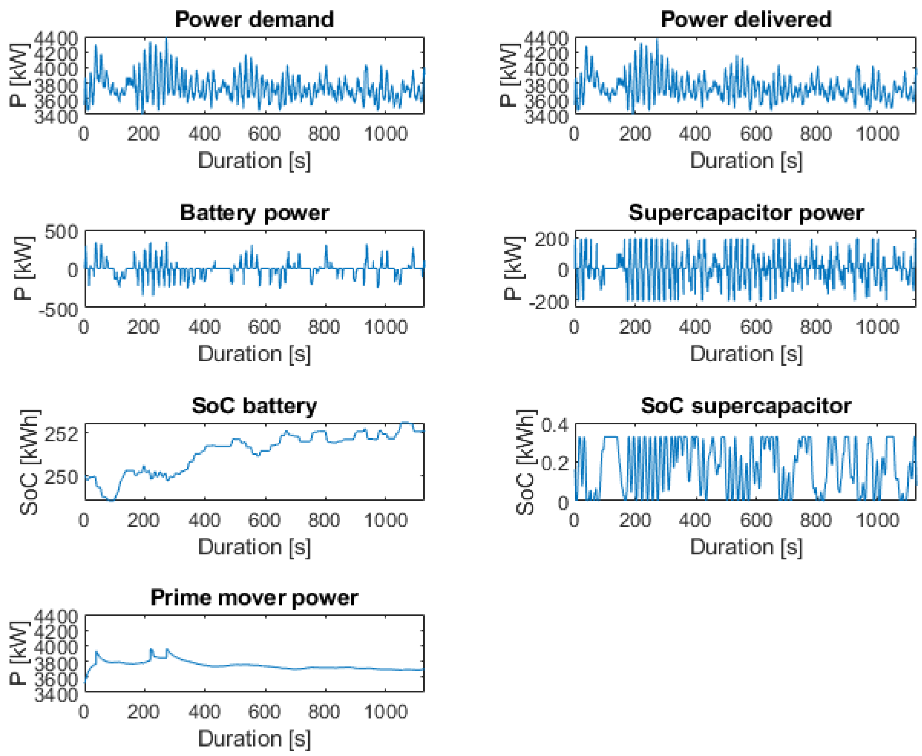


Figure 7.11: Propulsion plant data (configuration A; without supercapacitor over(dis)charge protection) during execution of test nr. 317

Firstly, a sensitivity analysis for rule 2 was performed. This is done in a similar approach as for rule 3. Test nr. 317 is used, with the corresponding y-coefficients shown in Table 6.1. Figure 7.15 shows the values for P_{SC}/P_B and the prime mover ramp rate for a series of x-coefficients for configuration A, C, G and I. The relative ESS use and the ramp rates are less correlated to the x-coefficients than to the y-coefficients in subsection 6.2.4. Besides, both the ramp rate and relative supercapacitor use increase drastically when increasing the x-coefficient.

To illustrate how this rule influences system behaviour an x-coefficient of 0.15 is implemented in Equation 6.1 and Equation 6.2. The results are shown in Figure 7.16. The battery use has become negligible, which means no degradation is induced. However, this is due to the fact that the prime mover will not allow the supercapacitor to exceed 80% or subceed 20% SoC and is continuously running at a power output close the demand power. The small power gap between the prime mover power output and power demand can be delivered by the supercapacitor, which makes the batteries obsolete. However, the mean ramp rate takes on values of around 150-200 kW/s, which is worse than without energy storage systems installed.

In the current implementation Rule 2 does not lead to the desired operational behaviour. section 9.4

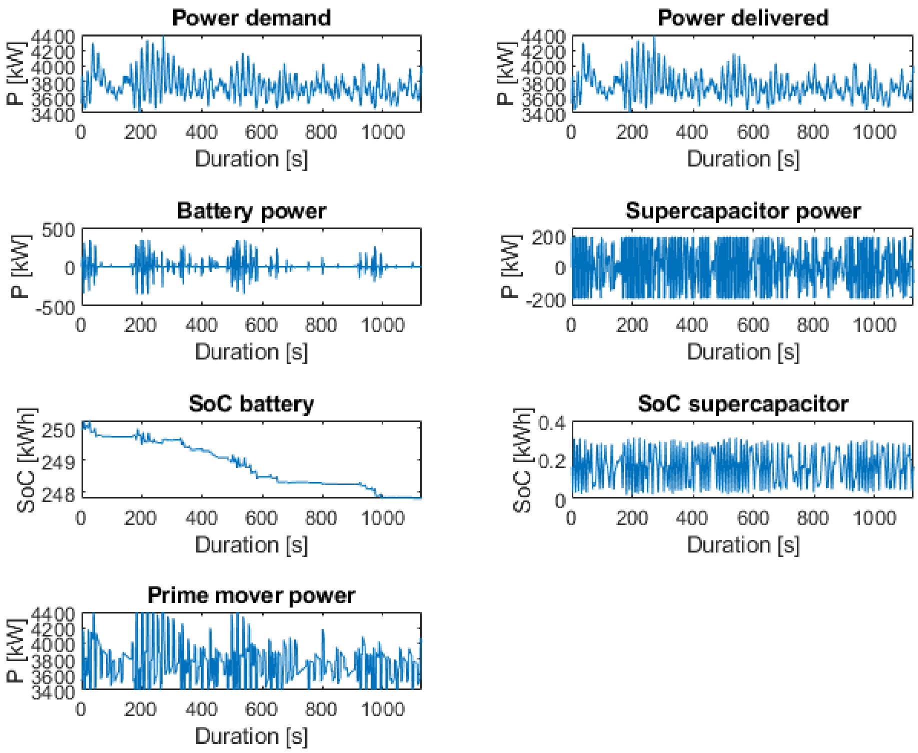


Figure 7.12: Propulsion plant data (configuration A; with supercapacitor over(dis)charge protection) during execution of test nr. 317

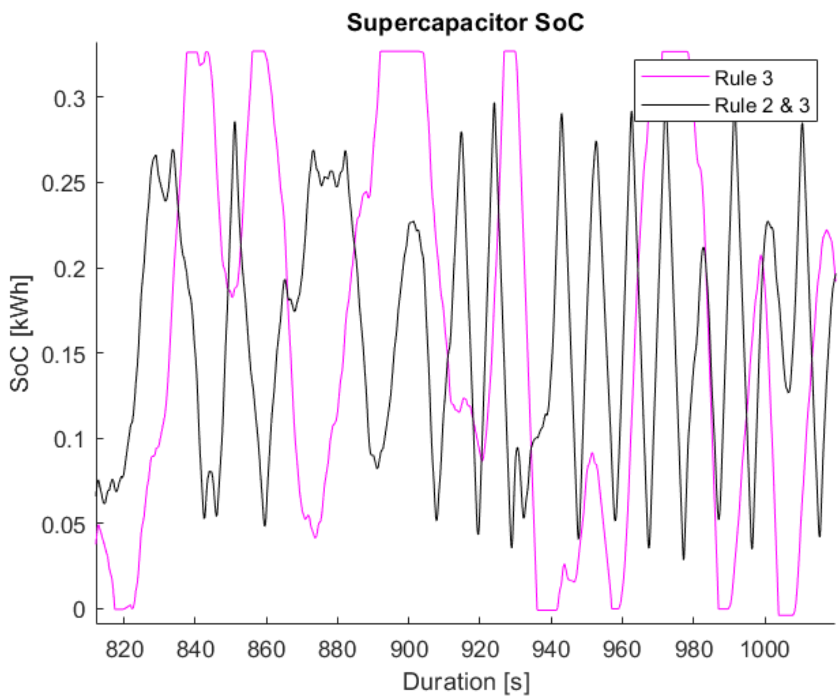


Figure 7.13: Supercapacitor SoC comparison during test nr. 317 for case 1 and 3

will further explain how this rule could be implemented in another way and lead to an improvement in power plant operations.

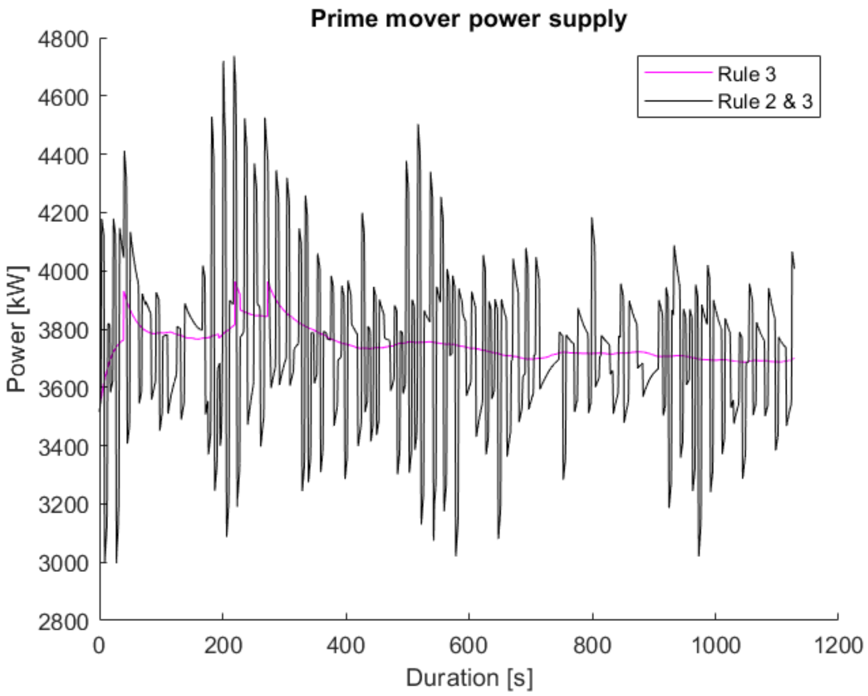


Figure 7.14: Prime mover power output comparison during test nr. 317 for case 1 and 3

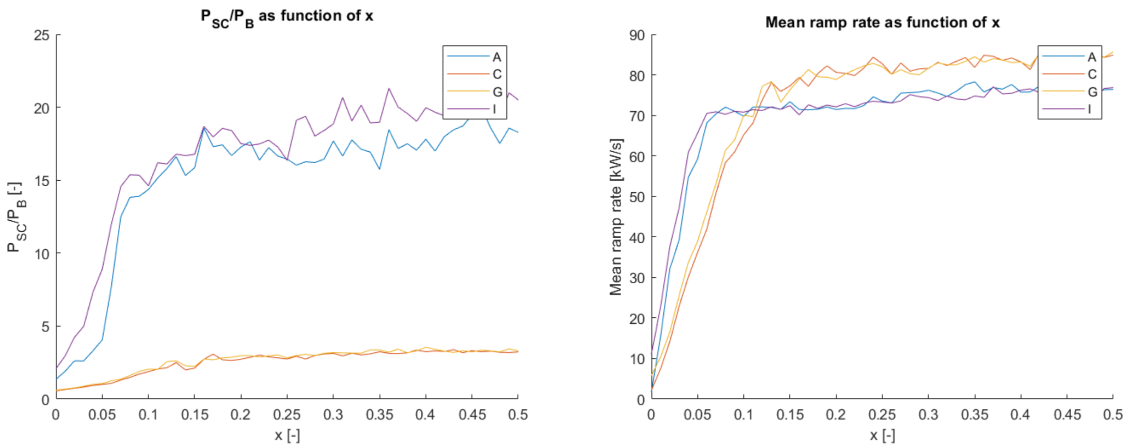


Figure 7.15: P_{SC}/P_B and mean ramp rate as function of the $x - coefficient$

7.4. Propulsion plant efficiency

An important propulsion plant performance parameter is the efficiency, which shows which part of the available energy is used for actual propulsion of the vessel. In the propulsion plant model three efficiencies are implemented. These are the round trip efficiencies for the battery and the supercapacitor bank and the DC-DC converter efficiency. They are respectively 95%, 95% and 98%. This means the total supercapcitor efficiency is 2% lower than the battery efficiency. Besides, the combined average ESS power for all configurations, in both Case 1 and 2, makes up around 2% of the total delivered power by the prime mover. Therefore, the losses that are introduced by storing energy in the supercapacitor bank compared to storing energy in the battery bank are negligible. This means there will be no significant difference among the configurations with regards to efficiency.

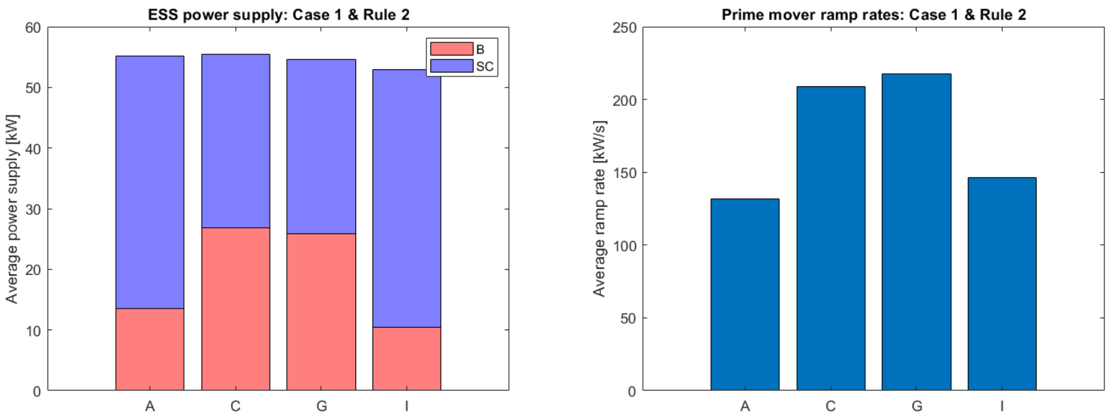


Figure 7.16: P_{SC}/P_B and mean ramp rate

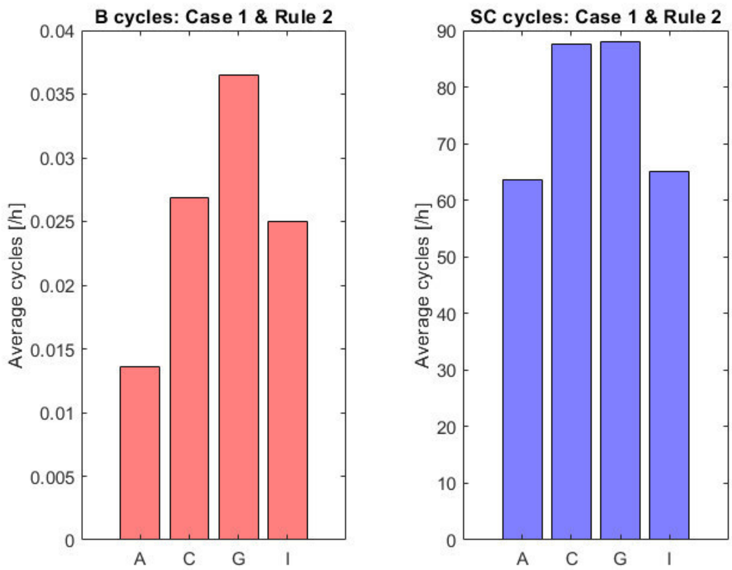


Figure 7.17: Supercapacitor and battery hourly cycles

8
Conclusion

Feadship is currently facing two challenges in yacht design. Firstly, battery capacity degradation occurs during load levelling in the diesel electric drive train. Secondly, the introduction of future prime movers, which show inferior ramping capabilities compared to the present day diesel engine, could require some form of power demand load levelling. In both these challenges supercapacitor energy storage, as an addition to battery energy storage, could offer a solution. This chapter will conclude this research and give a final verdict about supercapacitor energy storage on board of yachts. The research question reads:

How can levelling wave-induced load fluctuations in yachts with supercapacitor energy storage contribute to battery capacity preservation and downsizing of the propulsion plant?

This question will be answered in four parts. First, section 8.1 will explain how supercapacitor energy storage can reduce battery use. Secondly, section 8.2 will explain how supercapacitor energy storage can reduce the system size and weight. Thirdly, section 8.3 will explain how the prime mover power demand changes when supercapacitor energy storage is applied. Lastly, section 8.4 will give a more general overview of supercapacitor energy storage on board of yachts and explain for who it could be suited.

In general three configuration cases can be identified. The reference case E, which is a hybrid drive train with batteries installed. The constant power cases F-I, which feature a hybrid drive train with a constant power combined battery supercapacitor energy storage system. Lastly, the added power cases A-D, which feature a hybrid drive train with batteries and additional supercapacitors installed.

8.1. Battery use reduction

A goal of this research was to investigate whether supercapacitor energy storage can contribute to battery capacity preservation. Since batteries suffer from capacity degradation when running through cycles, the target was to find out whether the use of supercapacitors could lower the battery cycles per unit time. For configurations A and I, in which 58% of battery power was added or replaced by supercapacitor power, the battery cycling dropped to respectively 25% and 43% of the reference case. Additionally, the drop in hourly cycles also holds for supercapacitors when installing relatively more supercapacitor power. Although these might not suffer from capacity degradation they do have a limited cycle lifetime. Therefore, one could argue that the configurations A and I are superior when taking into account combined ESS lifetime, compared to the remainder of the cases.

Additionally, a C-rate dependence was observed when evaluating battery use. Lowering the C-rate, while maintaining the nominal power output in order to create a bigger energy capacity, reduces battery interference. In case 2, where the C-rate was 200 instead of 625, the battery cycling dropped to 16% and 34% of the reference case.

8.2. Combined ESS weight and volume

Current Feadship battery packs are designed on nominal power output, not on energy capacity. This introduces an energy capacity surplus which is not required for operation. In other words, the energy density of the battery bank is higher than the design requires. An additional energy storage system which features a higher power density than batteries can be used to match the power and energy requirements, while simultaneously lowering the weight and volume of the combined energy storage system. Therefore, a supercapacitor can be used to convert the battery energy capacity surplus into weight and volume savings.

In the constant power configurations this leads to weight and volume savings of 56% and 54% compared to configuration E. In the added power configurations volume and weight are increased by 4% and 2%. However, the combined ESS in configuration A features the same power output as a battery bank of 7142 kg and 6.044 m^3. This corresponds to a weight and volume reduction of 35% and 34%.

8.3. Prime mover ramping behaviour

In order to meet emission requirements it is likely that Feadships will be equipped with fuel cells or gas drives in the future. However, compared to the traditional diesel engine or generator these perform worse or not at all under transient loads. Therefore, it might be required to level the load demand in order for these prime movers to operate as designed. In this research the prime mover ramping behaviour is evaluated, not optimised, by using the mean ramp rate.

For the added power configurations the ramp rate decreased to 37% for configuration A. For the constant power cases the ramp rate increased to 398% for configuration I. The increase is due to the fact that the supercapacitor power output is not available when (de)saturated and therefore requires battery and prime mover power adjustments. Therefore, it could be argued that an increased energy capacity would lead to a higher supercapacitor operability. Case 2 confirms this. For respectively the added power cases and the constant power cases ramp rates of 27% and 229% of configuration E were observed.

8.4. General potential of supercapacitor energy storage on yachts

Supercapacitor energy storage introduces trade-offs in yacht design. Whether supercapacitor energy storage will be beneficial, is mostly depending on the vessel requirements and the owners preferences. Combined supercapacitor battery energy storage, compared to the conventional battery only energy storage, will reduce the amount of battery cycling. This will likely lead to battery capacity preservation, which will be elaborated upon in section 9.5. However, the extent till which battery cycling will be prevented is highly depending on the vessels operation area. The potential is higher in a vessel that frequently sails in waves, compared to a vessel that will be mostly stationary or sailing short trips in calm seas.

Additionally, supercapacitor energy storage can introduce weight and volume savings (configuration F-I) or reduce prime mover ramping (configuration A-D). Which option is better depends on the owners preferences and therefore, no unambiguous judgement can be made. If a design requirement is maximising guest space the energy storage pack size can be reduced by removing batteries. If the design incorporates an SOFC in the propulsion, additional load levelling can be achieved by adding supercapacitor power.

9
Discussion

This research provides first insights into the use of supercapacitor energy storage on board of Feadships. Additional research is required to fully evaluate the added value of supercapacitor energy storage and to identify specifically for who or which vessels it is suited. chapter 8 provides observations that can be used for this. However, in order to fully verify these conclusions some subjects require more elaboration. This chapter will discuss why these subjects require additional research and what can be done in order to get more realistic results.

9.1. Conservative environmental conditions

In chapter 4 the scatter diagrams for ship types A, B and C are discussed. These scatter diagrams consist of yearly averages, whereas the Feadships will only reside in these areas for a part of the year. Besides, the captains might try to avoid sailing in stormy weather. Taking these two matters into account, the scatter diagrams are likely conservative.

Besides, the time traces from MARIN do not cover the entire scatter diagrams, but only the harsh conditions. This too will lead to conservative results.

In order to increase reliability a separate study into the actually encountered sea states could be performed based on AIS and weather data. Another option is using actual propulsion power data of existing Feadships. This data will include the environmental conditions for specific seasons and the decisions made by the captain with regards to evading certain conditions. Therefore, this data could immediately be used in simulations without further pre-processing measures.

9.2. Power management

In order to guarantee the required level of quality for this research, it was decided to focus on the energy management in a yacht. Power management has not been included in this research. However, power management is a vital part for the use of supercapacitor energy storage on board of yachts. If further evaluation of supercapacitor energy storage is considered it is beneficial to model the electric grid and the corresponding power electronics. Complementing the energy management with power management simulations will be a big step into verifying the practical feasibility of supercapacitor energy storage.

9.3. Ramp evaluation

The prime mover ramp rate in this research is evaluated by using the mean ramp rate. This implies a linear effect between the ramp rate and the harmful consequences with regards to emissions, wear and tear or efficiency. However, this is rarely the case. In order to give a true value judgement with regards to prime mover ramping a dedicated cost function should be set up. This cost function should incorporate the specific physical effects as observed in experiments.

9.4. Rule 2 and additional energy management strategies

As observed in section 7.3 the use of supercapacitor over(dis)charge protection (Rule 2) in the simulations has little to no effect on the relative battery and supercapacitor use. However, it is highly counterproductive in terms of prime mover ramp rates. Rule 2 operates locally, when the SoC subceeds or exceeds a certain value. However, the sensivity analysis in this report is performed globally, which could be an explanation why the rule did serve its intended purpose. Setting up a dedicated implementation strategy for Rule 2 might prevent load steps which need to be delivered by the prime mover. Please note such load steps might not even be notable in the mean ramp rate, while they could be observed with a fitting ramping evaluation strategy as described in section 9.3, since load steps can lead to prime mover damage or stall.

Many more additional energy management strategies can be implemented in the evaluation of supercapacitor energy storage. The current energy management consists of a rule based control which was deemed suitable for this research. However, more sophisticated methods can be used. A derivation of the Equivalent Consumption Minimization Strategy could be used in which the cost function does not concern fuel use, but battery degradation or prime mover ramping. Also a heuristic approach could lead to better results in which the algorithm behind energy management can be optimised for a specific propulsion plant requirement.

9.5. Battery degradation

The effect of supercapacitor energy storage on battery power and cycles has been investigated during this research. However, this research provides no information on the expected operational lifetime, since battery degradation is not linearly related to average power supply. Battery capacity degradation depends on calendar and cycle aging. The former depends on time, the latter on use. First, due to calendar aging, an average power supply of 0 W still induces capacity degradation. Secondly, cycle aging is a non-linear process. Among others, it depends on the depth of discharge, mean state of charge, the battery age, environmental conditions and the (dis)charge amperage [7].

A more extensive model including energy and power management is required to determine these parameters. Additionally, this model should include long term power fluctuations which will have a significant impact on capacity degradation, due to the higher depth of discharge. An example is operating the yacht at night at battery power.

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A

Wave scatter diagrams

	North Atlantic *source GWS*						**Annual, All Directions**					
Hs (m)		**4**	**30**	**127**	**248**	**270**	**183**	**89**	**34**	**9**		**994**
> 14												
13-14												
12-13												
11-12												
10-11							1	1	1			**3**
9-10						1	1	1	1			**4**
8-9					1	2	3	2	2	1		**11**
7-8					1	4	5	5	2	1		**18**
6-7				1	3	9	11	8	4	1		**37**
5-6				2	9	19	20	13	6	2		**71**
4-5				5	21	38	34	19	7	2		**126**
3-4			1	13	46	65	47	21	6	1		**200**
2-3			4	32	78	80	43	15	4	1		**257**
1-2		1	12	53	76	48	17	4	1			**212**
0-1		3	13	21	13	4	1					**55**
	< 4	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**> 13**	**Tz (s)**

Figure A.1: Scatter diagram Northern Atlantic

	North Sea *source GWS*						Annual, All Directions					
Hs (m)	**22**	**160**	**324**	**290**	**147**	**49**	**12**	**2**				**1006**
> 14												
13-14												
12-13												
11-12												
10-11												
9-10					1							**1**
8-9				1	1	1						**3**
7-8			1	2	2	1						**6**
6-7			2	4	4	2	1					**13**
5-6		1	4	9	8	4	1					**27**
4-5		2	11	19	15	6	2					**55**
3-4		6	27	39	26	10	3	1				**112**
2-3	1	17	63	74	40	13	3	1				**212**
1-2	3	48	121	100	40	10	2					**324**
0-1	18	86	95	42	10	2						**253**
	< 4	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**> 13**	**Tz (s)**

Figure A.2: Scatter diagram North Sea

	Western Mediterranean *Area 26 GWS*							Annual, All Directions				
Hs (m)	**65**	**260**	**346**	**218**	**82**	**23**	**4**					**998**
> 14												
13-14												
12-13												
11-12												
10-11												
9-10												
8-9												
7-8				1	1							**2**
6-7			1	2	1	1						**5**
5-6		1	3	5	3	1						**13**
4-5		3	10	12	7	3	1					**36**
3-4	1	9	27	28	14	5	1					**85**
2-3	3	32	72	58	24	7	1					**197**
1-2	13	95	145	83	26	5	1					**368**
0-1	48	120	88	29	6	1						**292**
	< 4	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**> 13**	**Tz (s)**

Figure A.3: Scatter diagram Western Mediterranean

	Atlantic, east of Florida, Area 33					tlantic, east of Florida, Area 3						
Hs (m)	**6**	**66**	**215**	**299**	**230**	**120**	**48**	**14**				**998**
> 14												
13-14												
12-13												
11-12												
10-11												
9-10												
8-9												
7-8												
6-7					1	1	1					**3**
5-6				2	3	3	2	1				**11**
4-5			2	7	10	9	5	2				**35**
3-4		1	9	26	33	23	11	4				**107**
2-3		5	38	81	77	43	18	5				**267**
1-2	1	25	105	142	91	38	10	2				**414**
0-1	5	35	61	41	15	3	1					**161**
	< 4	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**> 13**	**Tz (s)**

Figure A.4: Scatter diagram Florida

	Caribbean Seas *Area 47 GWS*							Annual, All Directions				
Hs (m)	**10**	**84**	**247**	**308**	**211**	**96**	**32**	**9**	**2**			**999**
> 14												
13-14												
12-13												
11-12												
10-11												
9-10												
8-9												
7-8						1						**1**
6-7					1	1	1					**3**
5-6				2	3	3	1	1				**10**
4-5			3	9	11	8	4	1				**36**
3-4		2	14	35	38	22	9	3	1			**124**
2-3		10	59	104	82	38	12	3	1			**309**
1-2	2	37	125	135	70	22	5	1				**397**
0-1	8	35	46	23	6	1						**119**
	< 4	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**12-13**	**> 13**	**Tz (s)**

Figure A.5: Scatter diagram Caribbean

B

Shaft power analyses: Cumulative distribution functions and accumulated power consumption

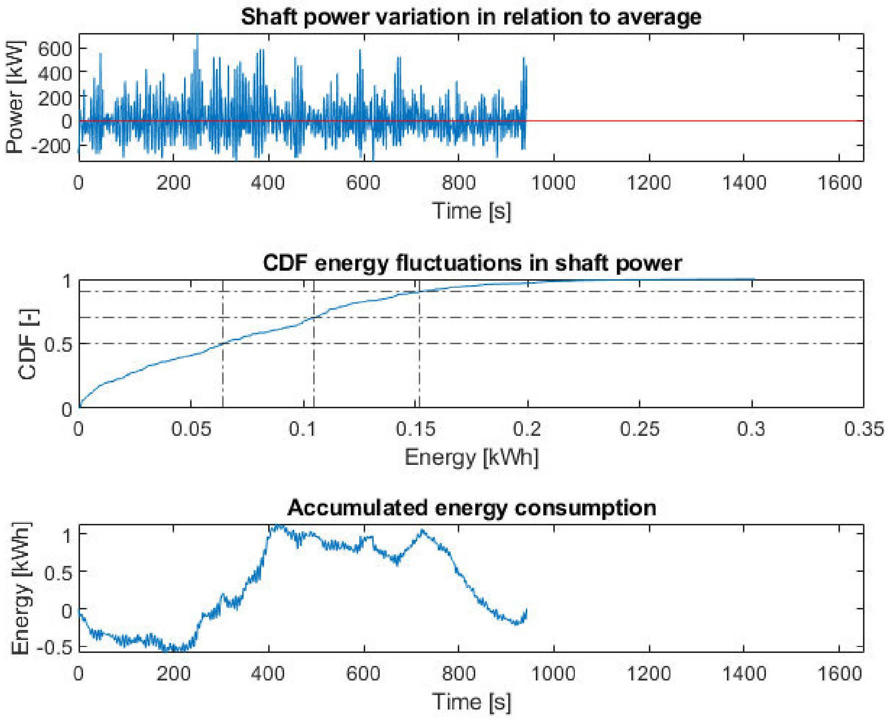

Figure B.1: Shaft power, CDF and accumulated power data for test nr. 310

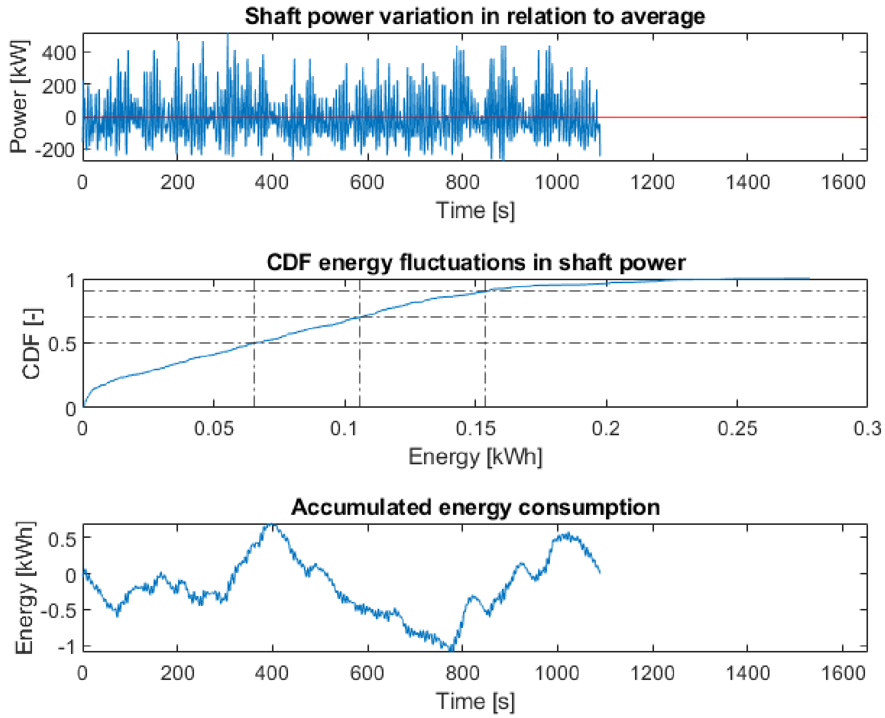

Figure B.2: Shaft power, CDF and accumulated power data for test nr. 311

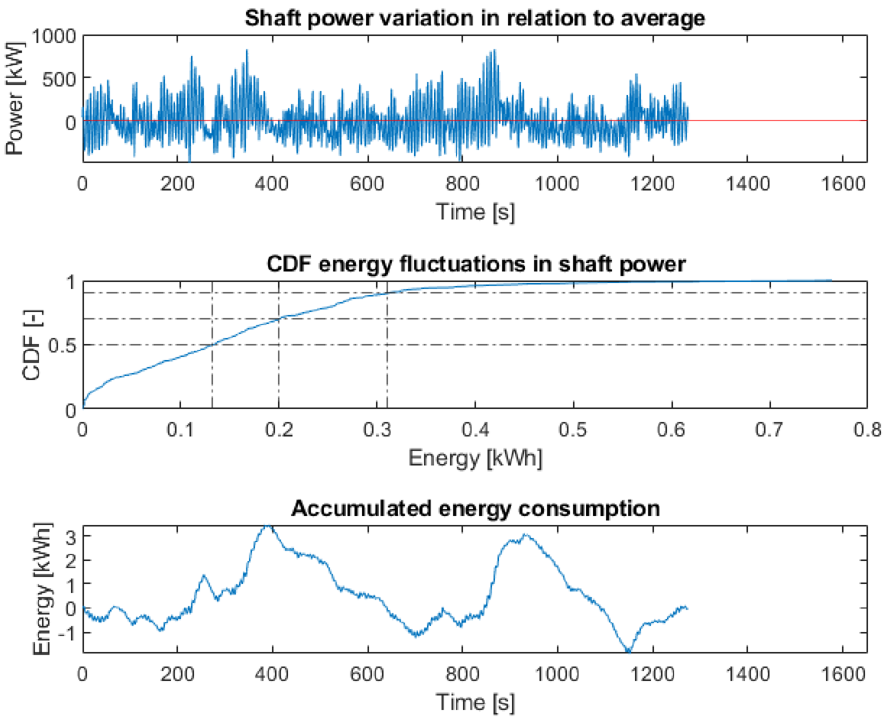

Figure B.3: Shaft power, CDF and accumulated power data for test nr. 312

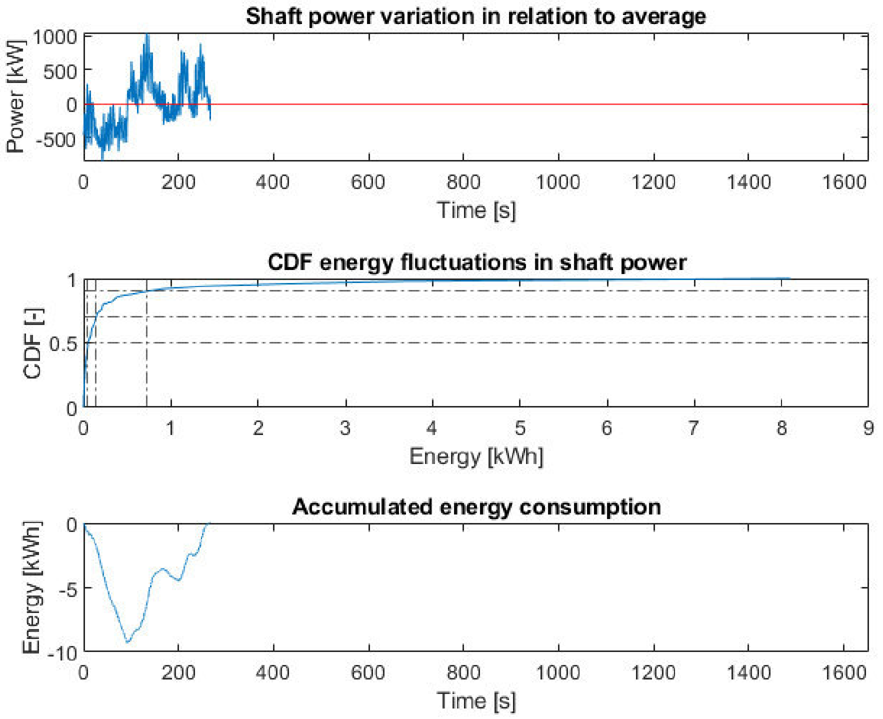

Figure B.4: Shaft power, CDF and accumulated power data for test nr. 313

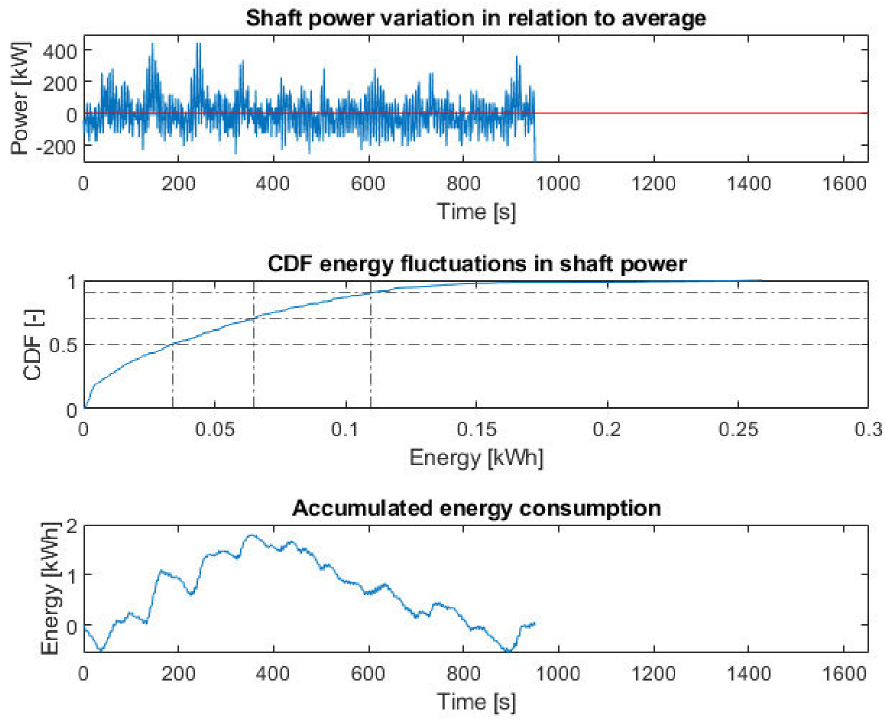

Figure B.5: Shaft power, CDF and accumulated power data for test nr. 314

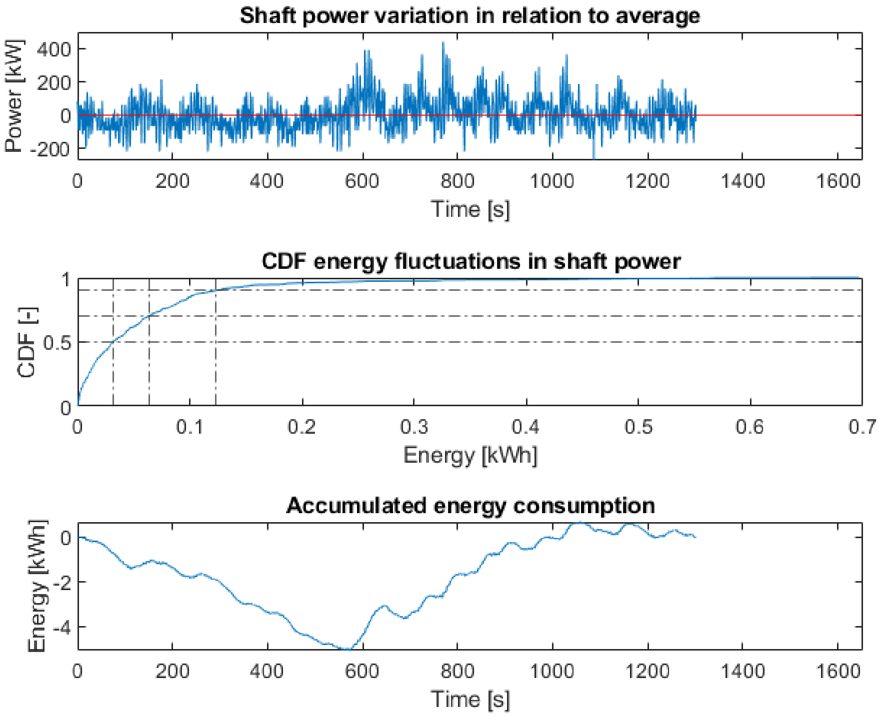

Figure B.6: Shaft power, CDF and accumulated power data for test nr. 315

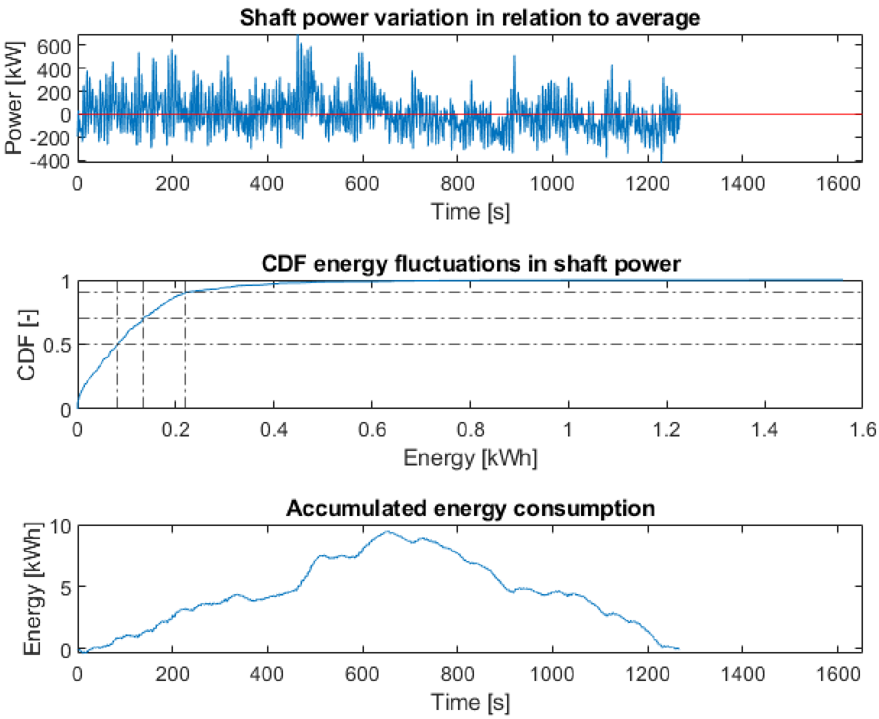

Figure B.7: Shaft power, CDF and accumulated power data for test nr. 316

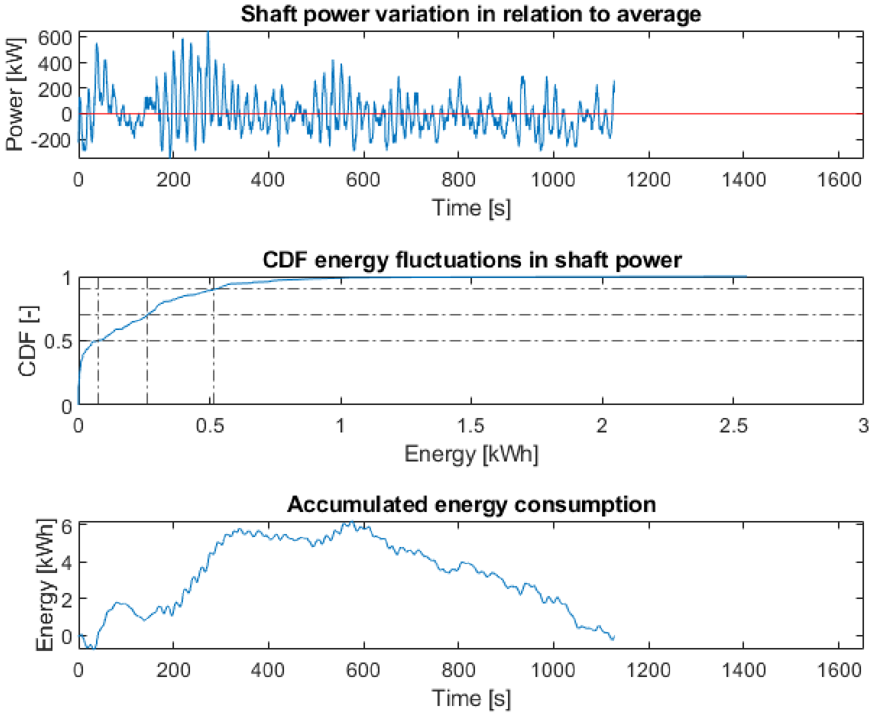

Figure B.8: Shaft power, CDF and accumulated power data for test nr. 317

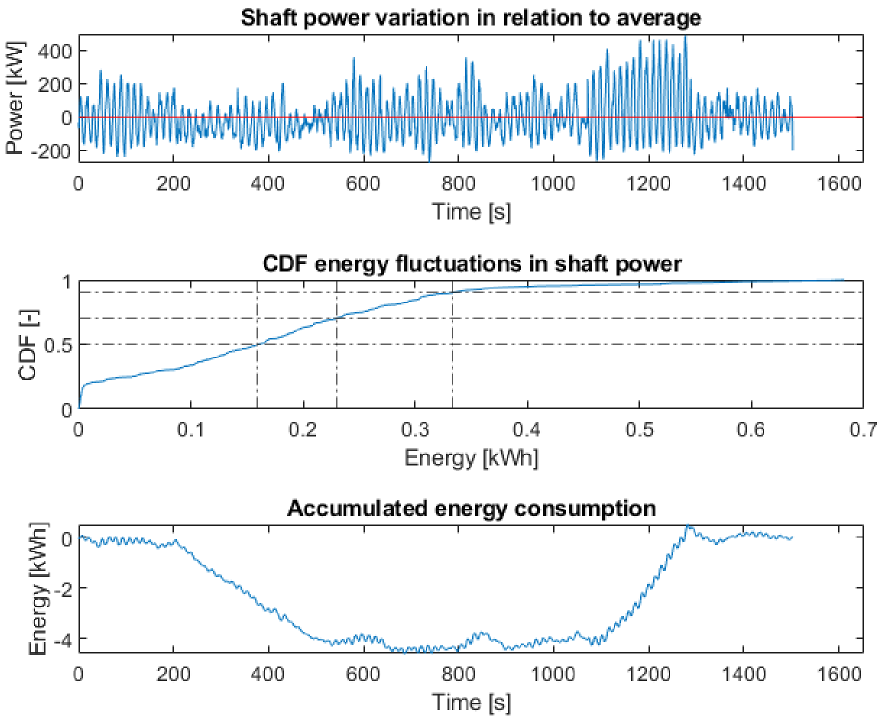

Figure B.9: Shaft power, CDF and accumulated power data for test nr. 319

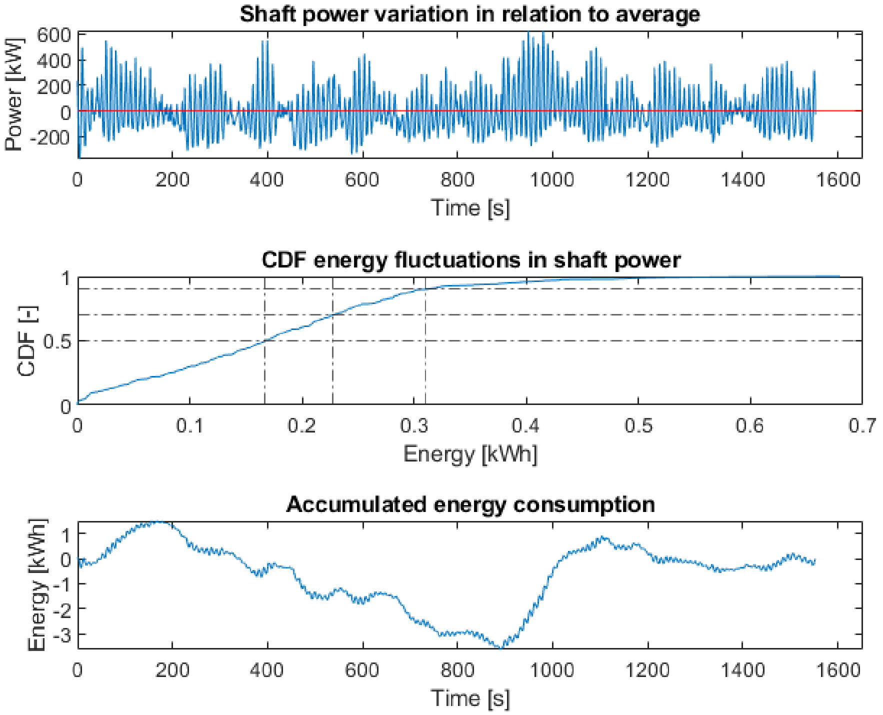

Figure B.10: Shaft power, CDF and accumulated power data for test nr. 321

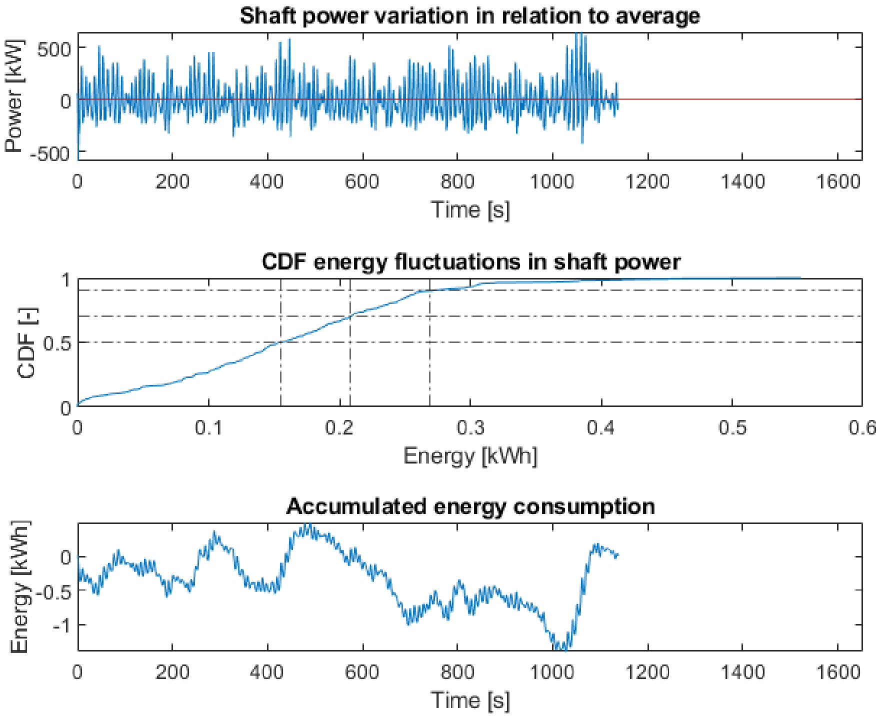

Figure B.11: Shaft power, CDF and accumulated power data for test nr. 322

C
Sensitivity analysis

Sensitivity analysis (case nr. 317)																				
A	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050									
P_SC/_P_B	0.3440	1.2670	1.4238	1.4149	1.4104	1.4128	1.4049	1.4015	1.3984	1.3941	1.3952									
Avg.ramp	1.1117	1.2686	1.3191	1.3217	1.4081	1.5415	1.6014	1.5952	1.6395	1.6783	1.7164									
B	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050									
P_SC/_P_B	0.2687	0.9087	0.9881	0.9902	0.9758	0.9677	0.9619	0.9571	0.9550	0.9536	0.9528									
Avg.ramp	1.2269	1.3886	1.4506	1.5138	1.5965	1.6569	1.7214	1.7773	1.8269	1.8702	1.9128									
C	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050									
P_SC/_P_B	0.1946	0.5602	0.5898	0.5856	0.5797	0.5777	0.5755	0.5743	0.5729	0.5728	0.5734									
Avg.ramp	1.2269	1.5089	1.5835	1.7173	1.8154	1.9358	2.0127	2.0807	2.1405	2.1948	2.2879									
D	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050									
P_SC/_P_B	0.1011	0.2554	0.2707	0.2648	0.2619	0.2606	0.2589	0.2584	0.2580	0.2577	0.2575									
Avg.ramp	1.4599	1.7617	1.9036	1.9967	2.0539	2.2173	2.3085	2.4158	2.4905	2.5579	2.6150									
E	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050									
P_B	*75.1717*	*56.2144*	*54.8968*	*54.6756*	*54.6524*	*54.6031*	*54.6297*	*54.6456*	*54.6245*	*54.6166*	*54.5874*									
Avg.ramp	1.6282	2.0246	2.2093	2.4062	2.5279	2.6953	2.8487	2.9574	3.0564	3.1498	3.2397									
F	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050									
P_SC/_P_B	0.1715	0.2511	0.2714	0.2745	0.2730	0.2702	0.2685	0.2677	0.2671	0.2662	0.2655									
Avg.ramp	2.3282	2.7372	2.9835	3.2144	3.4218	3.5893	3.7764	3.9334	4.0710	4.2068	4.2462									
G	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050									
P_SC/_P_B	0.4169	0.5332	0.5931	0.6115	0.6205	0.6208	0.6219	0.6207	0.6209	0.6193	0.6180									
Avg.ramp	3.7216	4.0941	4.1712	4.5466	4.8540	5.0679	5.2740	5.4226	5.6423	5.7222	5.8548									
H	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050	0.0055	0.0060	0.0065	0.0070	0.0075	0.0080	0.0085	0.0090	0.0095	0.0100
P_SC/_P_B	0.7710	0.9354	1.0819	1.1315	1.1563	1.1593	1.1579	1.1513	1.1575	1.1558	1.1538	1.1478	1.1433	1.1382	1.1334	1.1272	1.1234	1.1201	1.1129	1.1086	1.1065
Avg.ramp	5.9613	6.2237	6.3762	6.7431	7.1558	7.3950	7.6301	7.7975	8.1471	8.1768	8.4049	8.5789	8.6132	8.7817	8.8772	8.9349	9.0473	9.1770	9.2441	9.3821	9.5721
I	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050	0.0055	0.0060	0.0065	0.0070	0.0075	0.0080	0.0085	0.0090	0.0095	0.0100
P_SC/_P_B	1.6704	1.8256	1.9824	2.0268	2.0983	2.1408	2.1489	2.1432	2.1423	2.1120	2.1032	2.0827	2.0599	2.0349	2.0131	1.9925	1.9739	1.9554	1.9387	1.9221	1.9147
Avg.ramp	9.3686	9.8047	9.6742	10.0096	10.6453	11.1515	11.5280	11.6567	11.8950	11.8980	12.2268	12.5044	12.5520	12.6310	12.7716	12.8282	12.9697	13.1607	13.3025	13.5020	13.6744

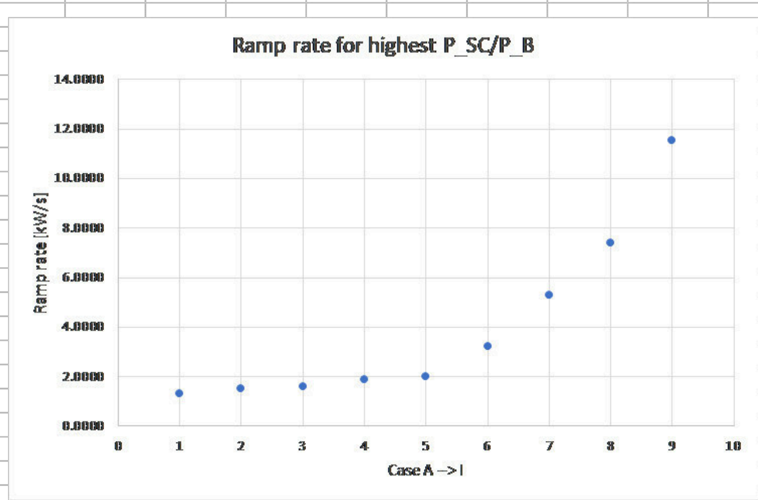

Figure C.1: Sensitivity analysis case 1

Sensitivity analysis (case nr. 317)																					
A	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050										
P_SC/_P_B	0.4815	2.1125	2.9083	3.3021	3.3830	3.3908	3.3789	3.3737	3.3982	3.3933	3.3082										
Avg.ramp	0.7188	0.8469	0.6891	0.6910	0.7012	0.7251	0.7595	0.7876	0.8291	0.8572	0.9820										
B	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050										
P_SC/_P_B	0.3478	1.1671	1.7343	1.9178	1.9798	2.0058	2.0185	2.0192	2.0213	2.0237	1.9794										
Avg.ramp	0.7454	0.9401	0.8166	0.9145	0.9720	1.0159	1.0552	1.0478	1.0857	1.1209	1.1874										
C	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050										
P_SC/_P_B	0.2353	0.7353	0.9682	1.0384	1.0602	1.0669	1.0725	1.0742	1.0776	1.0569	1.0577										
Avg.ramp	0.8295	1.0706	1.0148	1.1388	1.2110	1.2695	1.3417	1.4246	1.4692	1.5148	1.5966										
D	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050										
P_SC/_P_B	0.1232	0.3406	0.4226	0.4341	0.4285	0.4306	0.4314	0.4326	0.4333	0.4334	0.4335										
Avg.ramp	1.1078	1.3026	1.3905	1.5124	1.5955	1.7033	1.7872	1.8860	1.9544	2.0143	2.1021										
E	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050										
P_B	*75.1717*	*56.2144*	*54.8968*	*54.6756*	*54.6524*	*54.6031*	*54.6297*	*54.6456*	*54.6245*	*54.6166*	*54.5874*										
Avg.ramp	1.6282	2.0246	2.2093	2.4062	2.5279	2.6953	2.8487	2.9574	3.0564	3.1498	3.2397										
F	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050										
P_SC/_P_B	0.2212	0.3627	0.4166	0.4324	0.4424	0.4473	0.4429	0.4441	0.4390	0.4403	0.4405										
Avg.ramp	1.9791	2.1269	2.1046	2.2593	2.4697	2.6526	2.7528	2.9082	2.9900	3.1295	3.2207										
G	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050										
P_SC/_P_B	0.7150	0.8937	1.0546	1.0615	1.0554	1.0743	1.1130	1.1190	1.1248	1.0920	1.0948										
Avg.ramp	2.7017	2.4060	2.2353	2.2889	2.4096	2.5513	2.7486	3.0589	3.1748	3.3422	3.4418										
H	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050	0.0055	0.0060	0.0065	0.0070	0.0075	0.0080	0.0085	0.0090	0.0095	0.0100
P_SC/_P_B	1.6329	2.0199	2.1716	2.2391	2.2378	2.1960	2.1945	2.2139	2.3021	2.2469	2.2205	2.2282	2.2368	2.2460	2.2485	2.2477	2.2549	2.2578	2.2561	2.2558	2.2212
Avg.ramp	2.5463	2.8004	2.5647	2.7579	2.7834	3.0037	3.1082	3.4569	3.6321	3.7064	4.0191	4.0591	4.1402	4.1703	4.3298	4.4248	4.5318	4.6400	4.7293	4.8071	4.9212
I	0.0000	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030	0.0035	0.0040	0.0045	0.0050	0.0055	0.0060	0.0065	0.0070	0.0075	0.0080	0.0085	0.0090	0.0095	0.0100
P_SC/_P_B	3.5721	4.1368	4.7051	4.9005	4.8881	4.7785	4.4715	4.5201	4.5382	4.4487	4.4664	4.4369	4.4249	4.4468	4.4547	4.4382	4.4251	4.4030	4.3844	4.3687	4.3565
Avg.ramp	3.7237	3.2381	3.2188	3.4227	3.4767	3.8030	4.0099	4.3292	4.4637	4.4274	4.8567	5.0094	5.0348	5.2080	5.3786	5.4635	5.5261	5.6106	5.7145	5.8823	5.9116

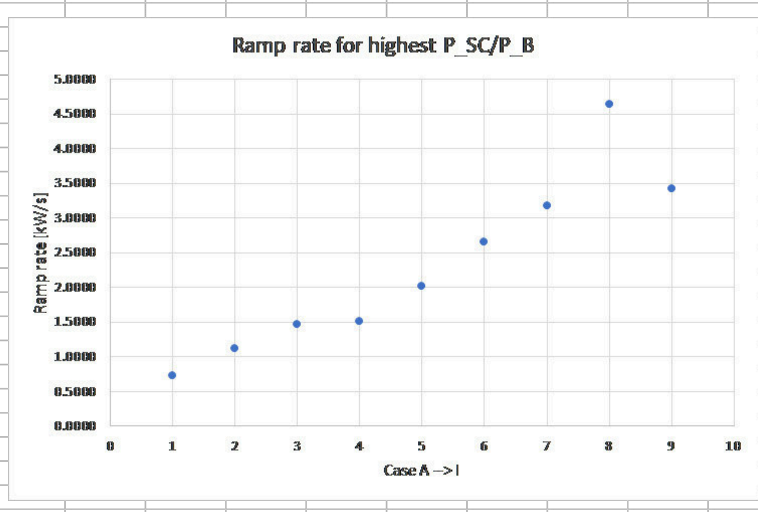

Figure C.2: Sensitivity analysis case 2

D

Literature review: Full report

Literature Research

Comparing different energy storage methods for load levellingstrn on board of diesel-electric yachts

Fons van den Elsen

Delft University of Technology

Literature Research

Comparing different energy storage methods for load levelling on board of diesel-electric yachts

F. van den Elsen

Master's programme
Marine Technology

January 14, 2022

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1
Introduction

In 2015 the United Nations (UN) set up the global sustainability goals, which function as a blueprint for peace and prosperity for people and the planet [1]. To contribute in achieving goal 13 (Climate Action) and 14 (Life Below Water) the IMO set up a target of reducing the greenhouse gas emissions of the global maritime fleet by 50% in the year of 2050. This corresponds to an 85% CO_2 emission reduction per ship on average [2]. The expected increase of the world fleet is taken account in this value. Besides, an increasing amount of people is concerned with their ecological footprint and less willing to purchase highly pollutant products. The new consensus when buying a yacht is starting to drift towards 'good for me, good for the planet', according to Roy [3]. Therefore, in order to remain relevant during the next decades, the yachting industry should drastically decrease its carbon footprint. Feadship is exploring ways to do so.

Lowering the environmental impact of a yacht can be done in multiple ways from the start of engineering till eventually the end of its lifetime. Building in a more sustainable facility, using more eco-friendly materials, realising a higher energy efficiency, sailing on alternative fuels and recycling or refitting the ship are some of the available methods.

This research will focus on the decrease of environmental impact during a yachts operational lifetime. It will investigate whether the fuel consumption and emissions can be decreased by using an alternative energy storage system (ESS). An ESS can be used to store energy for later use. The ESS will be used for increasing the diesel generator fuel efficiency, or for facilitating the implementation of more environmental friendly prime movers, like fuel cells. These often have inferior ramping capabilities compared to diesel engines and therefore could require an ESS for operation. Nowadays the most well known ESS in transportation is a lithium-ion battery pack. However, other types with different power storing properties will be discussed and evaluated.

This literature research will serve as the knowledge gap identifier for the main research *Comparing different energy storage methods for load levelling on board of diesel electric yachts*. The main research will cover several ESS' and compare them in terms of the influence on the system performance, efficiency, emissions and behaviour.

In chapter 2 the current state of the art power plants in yachts are discussed. This will be the power plant in which the different types of ESS' will be compared. In chapter 3 the power demand of a typical yacht will be discussed. A division will be made between hotel and propulsion loads. In chapter 4 the relevance of energy management and different types will be discussed. In chapter 5 diesel generators on board of diesel electric yachts and their working principles will be discussed. Besides, the implementation of additional prime movers will be addressed. In chapter 6 the most suited ESS' will be determined. This chapter will support why certain ESS' are suitable for operation on a yacht and why others are not. In chapter 7, chapter 8 and chapter 9 the lithium-ion batteries, flywheels, capacitors and supercapacitors will be explained more thoroughly. The relevant characteristics that will be needed to model these systems will be covered. Practical matter for implementation of these systems will be discussed too. In chapter 10 a final overview of lithium-ion batteries and the ESS' of choice will be given. Lastly, in chapter 11 the overall findings of this literature review will be presented. Besides, the knowledge gaps and research questions for the main research will be discussed.

2

Power plant

Present day power plants can be divided in two types: mechanical and electrical concepts. For Feadship these correspond to the diesel direct and diesel electric set up. In this chapter these set ups will be discussed. The following questions will be answered. What are the working principles of the two systems? How do they compare in terms of (dis)advantages? Which set-up(s) can be expected in the future?

2.1. Power plant types

Currently the biggest part of merchant ships is driven by a mechanic drive train, either direct or geared. This means each propulsor is powered by one or multiple diesel engines, which are mechanically connected by a propeller shaft and possibly a gearbox. Auxiliary systems on board of these ships are powered by a separate set of diesel generators and occasionally by a shaft generator (SG).

However, with sustainability being more valuated than ever before, the mechanical drive train is losing ground to the electrical drive train [4]. In the electric drive train a set of generators (possibly of varying sizes) power the grid. This is the same grid where all consumers are connected to, meaning that the separation of the propulsion and auxiliary drive train is no longer present. All systems are connected and virtually any prime mover can be used for powering any consumer on the ship, as shown in Figure 2.2 [5] [6]. Subsequently all power required for operation is taken from the same grid. From propulsive power, to lighting to HVAC systems. This leads to a wide spectrum of users and many (fluctuating) loads throughout the day. An evaluation of the power demand, can be found in chapter 3.

For a mechanical drive train, an engine at every shaft or auxiliary system should be running. In Figure 2.1 an example of a mechanical drive train is shown.

In both concepts an additional energy storage system (ESS) can be included, with batteries often being the preferred choice.

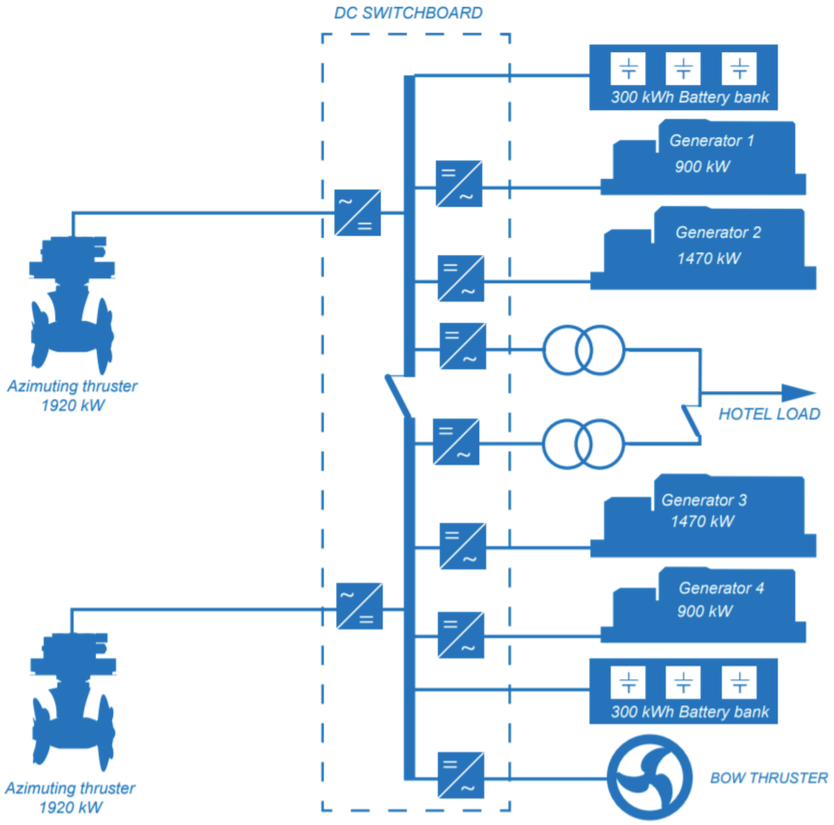

Figure 2.1: Diesel electric setup [7]

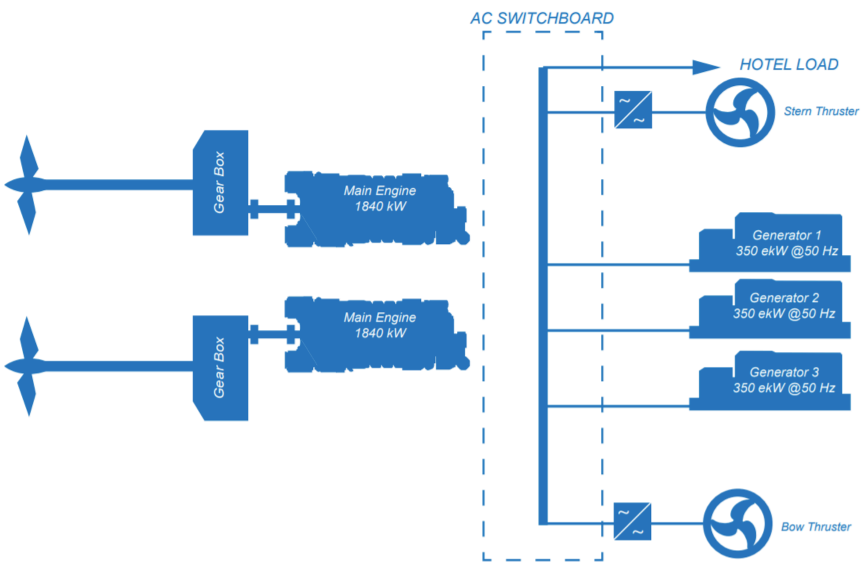

Figure 2.2: Diesel direct set up [7]

2.2. Trade-offs

The switch from mechanical to electrical drive trains is not happening without a reason. In subsection 2.2.1 and subsection 2.2.2 the main advantages and disadvantages for electric drive trains will be discussed.

2.2.1. Advantages electric drive train

One of the biggest differences between the electrical and the mechanical drive train is the lack of the mechanical connection between the prime mover and the propeller. This comes with numerous benefits. First, it gives more freedom in design of the ship. The engine and propeller no longer have to be placed along the same axis. Therefore, the alignment of the engines is no longer critical and more vibration mitigation measures, like double-sprung mountings, can be applied. Secondly, this is accompanied by the fact that generators are used, which run at either one or a few fixed speeds. This too makes the implementation of vibration mitigating designs less complicated. Thirdly, since multiple generators can be turned on or off, it's possible to stay close to the design points and therefore maintain a higher fuel efficiency, as shown in Figure 2.3. Combining this with an ESS to account for the power surplus or shortage will even more often guarantee that each generator is running in its design point. This way the power plant can have multiple design points, which is beneficial when dealing with a varying operational profile. Lastly, all electric ships (AES) offer advantages in the field of energy and/or power sources. The infrastructure that is required for installing an electric energy source, like solar, wind or a fuel cell is already present. Therefore, AES offer opportunities either for retrofitting or when re-using and adjusting an already existing building plan [4] [6] [8].

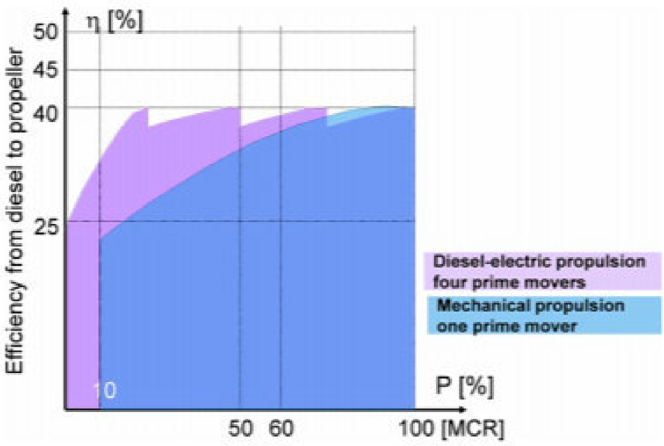

Figure 2.3: Drive train efficiency as function of power output [8]

2.2.2. Disadvantages electric drive train

However, an electric drive train comes with disadvantages too. Firstly, all power generated needs to be converted. This means that conversion losses are always present. According to Loon and Zon [9] a diesel electric propulsion system uses around 10% more fuel at top speed. The break even point is around cruising speed, below this speed the conversion losses can be compensated for by optimal generator loading. Secondly, an electric drive train requires more components and casings. This could nullify the fact that space is saved, by placing the generator in the most convenient place.

2.3. Future Outlook

The message that should be taken from this chapter is that electric drive trains are increasingly preferred over mechanical drive trains. Nowadays electric drive trains can, among others, be found in icebreakers, superyachts, dredgers, pipe layers, cable layers, ferries, LNG carriers and cruise liners. For the latter, nowadays even 100% of the newly built vessels are AES, additionally some older vessels have been retrofitted with an electric drive train [4] [8]. A common denominator of these vessels is they either have a varying load profile with multiple working points, or they have a relatively high hotel load with many electric consumers. This requires a power plant that can efficiently provide in power over a wide range of operations.

Since both of these factors do apply for yachts, this review will be focused on the diesel electric drive train on board of yachts.

3

Power demand of a typical yacht

The typical operational profile, based on the experience of De Voogt, is shown in Table 3.1. Sailing accounts for 10% of the time [7].[1] However, due to the increased power demand during sailing, around 50% of the available fuel will be used for it. The remaining 50% of fuel is used for hotel purposes. This means fuel savings in both purposes can be significant. Therefore, both the hotel and propulsive loads will be considered with regards to the use of an ESS.

Table 3.1: Typical operational profile of a yacht. [7]

Operation	Relative duration
1. Sailing	10%
2. Manoeuvring 3. Dynamic positioning	5%
4. At anchor	25%
5. Harbour 6. Shore conversion	60%

Since an ESS is used to store energy for later use, it is only useful in dynamic systems. Evaluating an ESS requires data with regards to the dynamic power demand. In section 3.1 till section 3.3 various operational modes and ways in which power fluctuations can be determined, are discussed. Due to a limited amount of data available, the data in this chapter originates from three vessels. However, only the relative and not absolute values are used. Therefore it is assumed the influence of the varying ship sizes is not significant.

3.1. Quasi-static electric power consumption

To gain insight into the power consumption on a typical yacht the electric consumers on board of a Feadship have been investigated. The operational profile is divided into six operational modes: sailing, manoeuvring, dynamic positioning (DP), harbour, at anchor (active stabilizers) and shore power. The static relative power demand for these modes is shown in figure Figure 3.1. The chart area relates to the total required power for said operational mode. The six largest consumer groups within each mode are shown. During manoeuvring and dynamic positioning the highest power is used, due to the manoeuvring systems. Among others, these consist of the bow and stern propeller and the stabilizer pack. Although the manoeuvring systems require the most power, they are not necessarily the most suitable for fuel saving or emission mitigation measures, since these systems are only engaged for a fraction of the time. Therefore, profits will be marginal.

The three largest consumers in each operational mode are the HVAC, the manoeuvring and the galley/pantry/laundry systems. In each mode these account for at least 71% of power consumption. In order to generate a dynamic power demand, the dynamic characteristics of these system components could be studied. These consumer groups, however, consist of respectively 62, 7 and 25

[1] Note that only a limited number of yachts is available and these numbers are rather owner dependent.

consumers, which makes determining a dynamic power profile time inefficient. Besides, the HVAC (biggest consumer) power is rather levelled and doesn't cause any sudden power peaks. Lastly, additional measurements are required for validation.

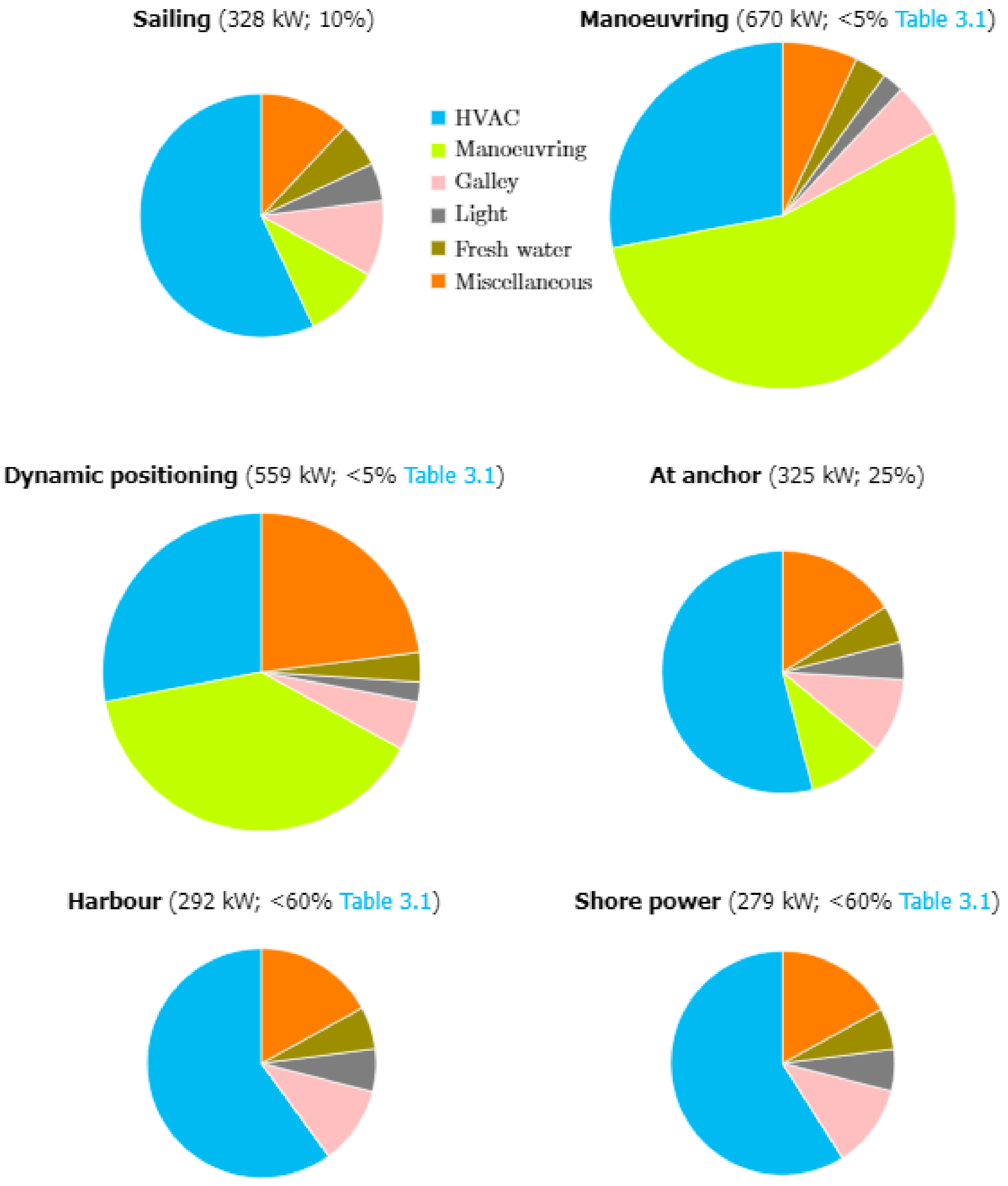

Figure 3.1: Relative energy consumption for sailing, manoeuvring, dynamic positioning, at anchor, harbour and shore power

3.2. Dynamic electric power supply

An alternative way of gaining insight into the dynamic power demand is by evaluating diesel generator data. Figure 3.2 and Figure 3.3 show a typical time trace of the power supply on board of a typical diesel direct Feadship during transit in calm seas. Only one diesel electric Feadship is built and no suitable data of this ship is available. Therefore the data of a diesel direct Feadship is used in this section.

In the main engine power output fluctuations with a period of 10-50 seconds can be identified. The power fluctuation band is limited to ~20 kW and more often to ~10 kW or less and is therefore close to 1% of nominal engine power. Levelling the load will lead to neglectable fuel savings that will not be able to compensate for the conversion losses in an ESS, which are in the order of a few percent. However, when sailing in higher sea states, the required power and fluctuations will be higher. This is discussed in section 3.3.

In the diesel generator power, peaks and troughs can be identified. The duration for both is 100-120 seconds. The power fluctuations are ~20 kW, which corresponds to ~10% of generator power.

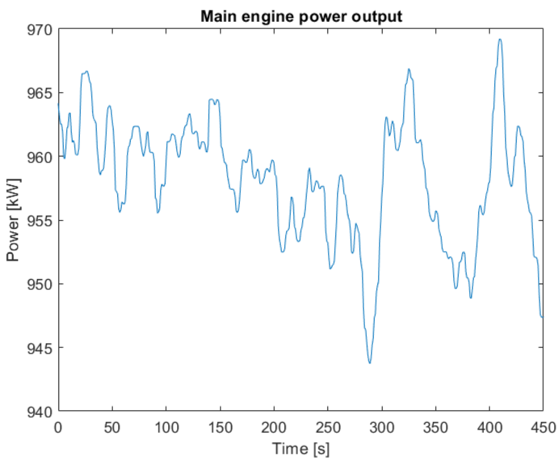

Figure 3.2: Main engine power output

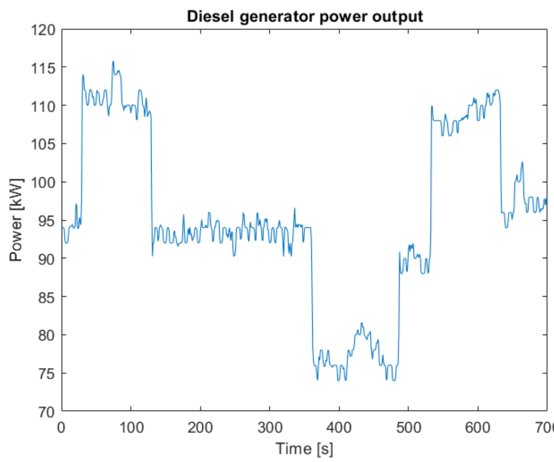

Figure 3.3: Diesel generator power output

3.3. Power demand in higher sea states

Yachts do not only encounter calm seas. During transits in higher sea states the ship resistance increases and subsequently the required propulsion power increases. Besides, the power fluctuations, which are positively correlated with wave height, increase. Figure 3.4 shows a wave distribution diagram for waves encountered by Feadships during a three year time interval in the Mediterranean and Caribbean. The graphs show a clear distinction between wave heights in the Mediterranean and Caribbean. In the former, 80% of the waves encountered are smaller than 1 m. In the latter, 80% of the waves encountered are between 1 m and 2 m. Sailing in calm seas is not occurring in the Caribbean. Therefore the evaluation of an additional ESS is especially important for ships sailing in the Caribbean.

For a diesel electric motoryacht, Marin has performed seakeeping model tests during transits in irregular waves. Among the results are the propeller thrust, torque and rpm for PS and SB drive train. Figure 3.5 shows these parameters during a 1300 second towing test. The engine rpm is fixed, thus the propeller torque and propeller power are linearly related. For this particular case, the power fluctuation period 6.5 seconds and they can reach up to ~20 percent of total power.

3.4. Opportunities for load levelling

The quasi-static power demand of hotel consumers will not be used to set up the total power demand for three reasons. Firstly, a high number of hotel consumers is involved in the total power consumption. Secondly, the dynamic behaviour of all hotel consumers should separately be studied and leaves room for uncertainties, which need to be validated. Thirdly, one of the biggest consumer systems, HVAC, will

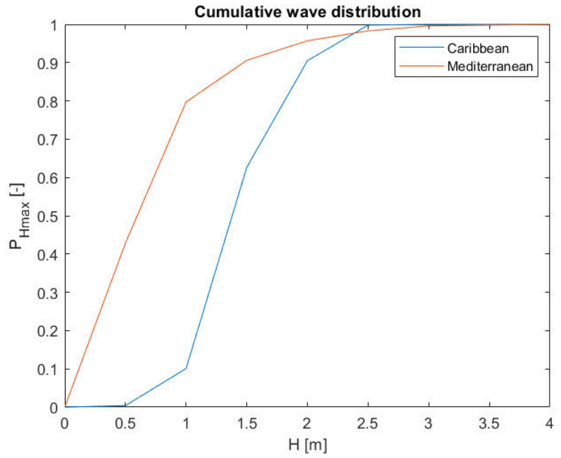

Figure 3.4: Accumulated wave distribution in Mediterranean and Caribbean

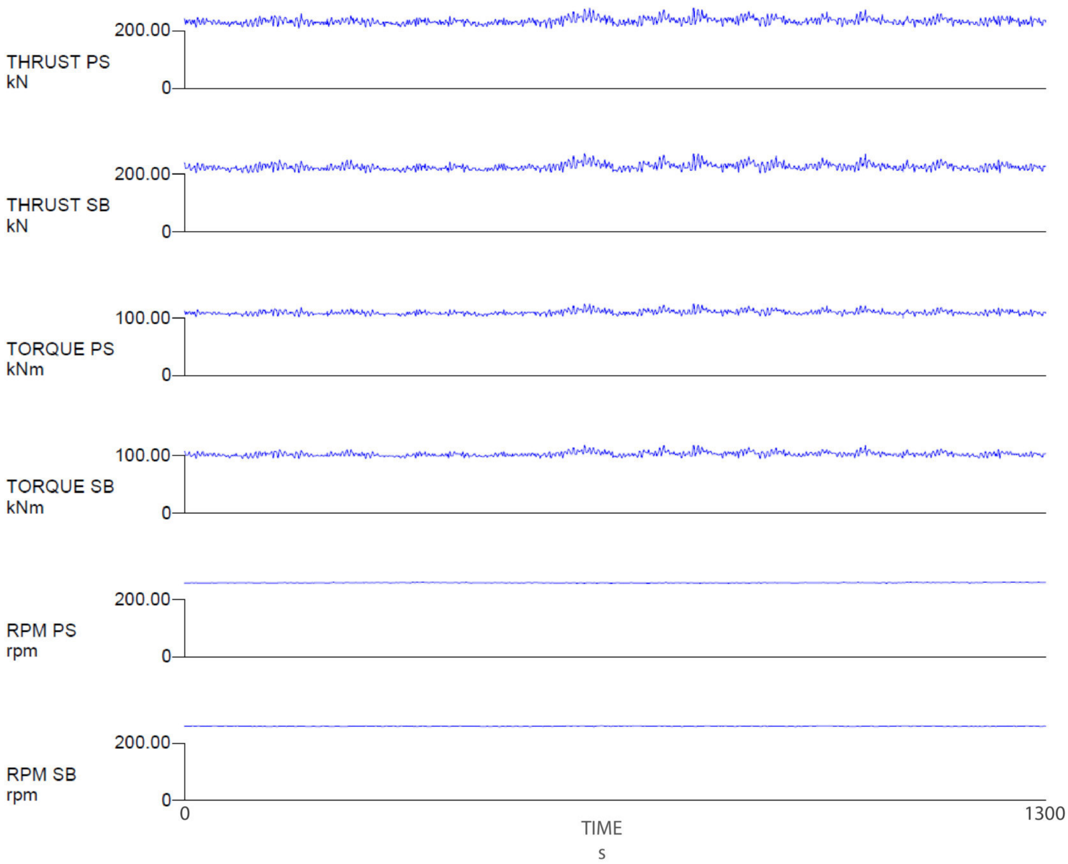

Figure 3.5: Thrust, torque and propeller rpm in head waves ($H_s = 2.5m; T_p = 10.0s; V_s = 15.1kn$)

not have a big dynamic influence on the system. Whereas dynamic load changes are a requirement for application of an ESS.

The data from section 3.2, section 3.3 and Figure 3.5 shows dynamic power fluctuations. Depending on the type of prime mover, it could be beneficial to level the peaks that are present in this data. In chapter 6 these peaks will be discussed in depth.

4

Energy Management

How a yacht power plant is used depends on the energy management strategy. Numerous strategies exist which all have their own advantages and disadvantages in terms of efficiency, computational complexity, operability etc. This chapter gives an overview of the available knowledge with regards to energy management. What is the use of energy management? Which methods are available and how do they work? What are the (dis)advantages of these methods?

4.1. Energy Management

The introduction of more components in the transmission lines of ships increases the degrees of freedom and the need for energy management. Nowadays, especially in hybrid and diesel electric vehicles, the drive train is so intertwined, that energy management is vital for operation. The Association of German Engineers maintains the following definition for energy management:

> *Energy management is the proactive, organized and systematic coordination of production [2], conversion, distribution and use of energy to meet the requirements, taking into account environmental and economic objectives [10].*

Within the scope of this research production happens in the prime mover(s), the conversion and distribution will happen in all system components between the prime mover and the consumers and the requirements can be seen as the yacht load profile. In most present day diesel-electric yachts the prime mover consists of multiple diesel generators. The environmental and economic objectives are the minimization of emissions and fuel consumption and an increase in the system durability. In order to achieve these or additional targets, numerous energy management strategies can be used. section 4.2 and section 4.3 cover rule-based control and the Equivalent Consumption Minimization Strategy.

4.2. Rule-based control

Rule-based control can be used for energy management. This method relies on a set of rules, which are based on heuristic knowlegde. For a hybrid vehicle such a rule could be: 'If SOC>80%, then turn off ICE and switch to electric propulsion'. Among the rule parameters that could be included in case of a diesel electric yacht are the ESS state of charge (SOC), engine speed, demanded ramp rate and power demand. This method is not optimal in terms of energy consumption or emissions, but it guarantees system functioning in a clear way [11] [12].

4.3. Equivalent Consumption Minimization Strategy

Limiting fuel consumption and emissions in a hybrid vehicle is a global problem, while the actions that can be taken are local. This problem cannot be solved without prior knowledge concerning the voyage. However, the Equivalent Consumption Minimization Strategy can approach this solution.

[2] VDI uses procurement instead of production, since this quote is originally referring to energy management in residential areas.

4.3.1. Working principle

In this method the instantaneous fuel consumption is minimized. During operation an equivalent fuel consumption cost function is determined based on the current system variables. This cost function depends on the type of system that must be described. Zhang et al. [13] use Equation 4.1, which gives the equivalent energy consumption for a fuel cell, battery and supercapacitor in a tram. In this equation the first term covers the energy used by the fuel cell. The second term covers the energy used by the battery, where k_1 is a penalty which increases when the SOC decreases. The third term covers the cost of supercapacitor use in a similar way as the second term. Since the supercapacitor is the only option when generating peak powers over short time, Zhang et al. [13] neglect the last term.

As can be seen from these examples the cost function is similar for different systems, but not the identical. The cost function should be tuned to fit its specific purpose in system with different cost criteria.

$$P_{fc} = min(C_{fc} + k_1 \cdot C_{bat} + k_2 \cdot C_{uc}) \tag{4.1}$$

In Equation 4.2 k_1 is shown. In this equation μ is the balance SOC, $SOC_{bat,max}$ and $SOC_{bat,min}$ are respectively the maximum and minimum allowable SOC.

$$k_1 = 1 - \mu \frac{SOC_{bat} - \frac{SOC_{bat,max}+SOC_{bat,min}}{2}}{\frac{SOC_{bat,max}+SOC_{bat,min}}{2}} \tag{4.2}$$

Pisu and Rizzoni [14] use function Equation 4.3. This function is similar to Equation 4.1. However, a penalty for nitrogen oxide emissions is included in which λ_{NOx} is the penalty for emissions and $\dot{m}_{NOx}$ is the amount of nitrogen oxide emitted.

$$\dot{m}_{f,eqv} = \dot{m}_f + f_{pen} \cdot \dot{m}_{f,em} + \lambda_{NOx} \cdot \dot{m}_{NOx} \tag{4.3}$$

4.3.2. Fuel saving effectiveness

According to Geertsma [12] the ECMS gives better results in terms of fuel consumption and CO_2 emissions over all investigated operating profiles of a typical tugboat, compared to the currently implemented rule-based controller. The ECMS decreases fuel consumption to within 1-2% of the global optimum, which is determined by means of dynamic programming. The ECMS can be supplemented with a receding horizon, which takes into account the end of the operational profile and adjusts the reference SOC accordingly. This way the entire battery capacity will be used during operation. Another suggestion for altering the conventional ECMS method is by adjusting the equivalence factor based on the remaining mission time. The A-ECMS set up in Geertsma [12] estimates the upcoming load variations based on a stochastic approach. Overall A-ECMS performs slightly better than ECMS (4.0% versus 3.7% fuel savings), but this is not consistent over all profiles. Over the typical profile ECMS leads to the highest savings, while A-ECMS performs better over low loads.

Pisu and Rizzoni [14] performed a similar research, albeit on a VW Motori 103 kW truck engine in combination with an 18/42-kW induction motor, and supports these findings. The A-ECMS outperformed rule-based control in both FUDS and FHDS (federal urban driving schedule; federal highway driving schedule) and showed results, similar to the global optimum, which was determined by dynamic programming. Besides Pisu and Rizzoni [14] discussed several qualitative aspects of the rule-based control and A-ECMS. All of which were in favour of the A-ECMS except for the following. When setting up an A-ECMS model, efficiency maps of various components are required in order for the cost function to be available, whereas the rule-based control only requires arbitrary breakpoints upon which the rules can be determined. However, with regards to tuning, computational complexity, portability and the number of tunable parameters A-ECMS is superior.

4.4. Energy management of choice

The A-ECMS is outperforming the rule-based control in terms of system efficiency. Besides, this method is relatively simple with regards to parameters and computational complexity. Therefore, the suitability of the ECMS will be investigated for comparing different ESS'.

5
Engine generators

Production and conversion of energy as used in section 4.1, are taking place in the generator sets. A generator set consists of a diesel engine and an induction motor, functioning as an electric generator. This chapter will give insight into the different types of generators, the corresponding working principles, the fuel consumption, the emissions and conversion losses.

5.1. Diesel engine

A diesel engine converts chemical energy into heat, which then, by means of a piston is converted into mechanical energy in the form of a rotating shaft. The shaft is connected to an electric generator which converts mechanical energy into electric energy. In the following sections the diesel engine and electric motor will be separately discussed. The net power delivered by the diesel engine is called the brake power (P_B), which depends on the shaft rotational velocity (ω) and the torque exerted by the shaft (T) as shown in Equation 5.1.

$$P_B = \omega \cdot T \tag{5.1}$$

Operating a diesel engine comes with several losses. The chemical energy going in (Q_f), is partly lost in combustion losses, cooling water or lubrication oil, exhaust gasses or friction. The remainder is useful work (W_e). The overall engine efficiency (η_e) is calculated as shown in Equation 5.2.

$$\eta_e = \frac{W_e}{Q_f} \tag{5.2}$$

Engine efficiencies are often expressed in the specific fuel consumption (sfc), which is inversely related to the engine efficiency. The sfc can be expressed in [kg/J] and [g/kWh], the latter being more commonly used. The calculation for both units are shown in respectively Equation 5.3 and Equation 5.4.

$$sfc = \frac{\dot{m}_f}{P_B} = \frac{m_f}{W_e} = \frac{1}{\eta_e \cdot h_L} \tag{5.3}$$

$$sfc = \frac{3600000 \cdot \dot{m}_f}{P_B} = \frac{3600000}{\eta_e \cdot h_L} \tag{5.4}$$

However, the ratio between W_e and Q_f is not constant, but depends on myriad factors, like engine speed, fuel flow, engine temperature, wear etc. Subsequently the engine efficiency and specific fuel consumption are not either. Varying external and internal operating conditions impact the magnitude of the losses. Therefore, engine manufacturers can set up an sfc diagram to show the efficiency as function of engine power and shaft speed. Such a diagram is shown in Figure 5.1. Modelling a diesel engine with an sfc diagram and a look up function minimizes computational complexity, compared to modelling separate losses as function of the operating conditions [5]. However, this method does not include the emissions and or fuel losses associated with transient behaviour.

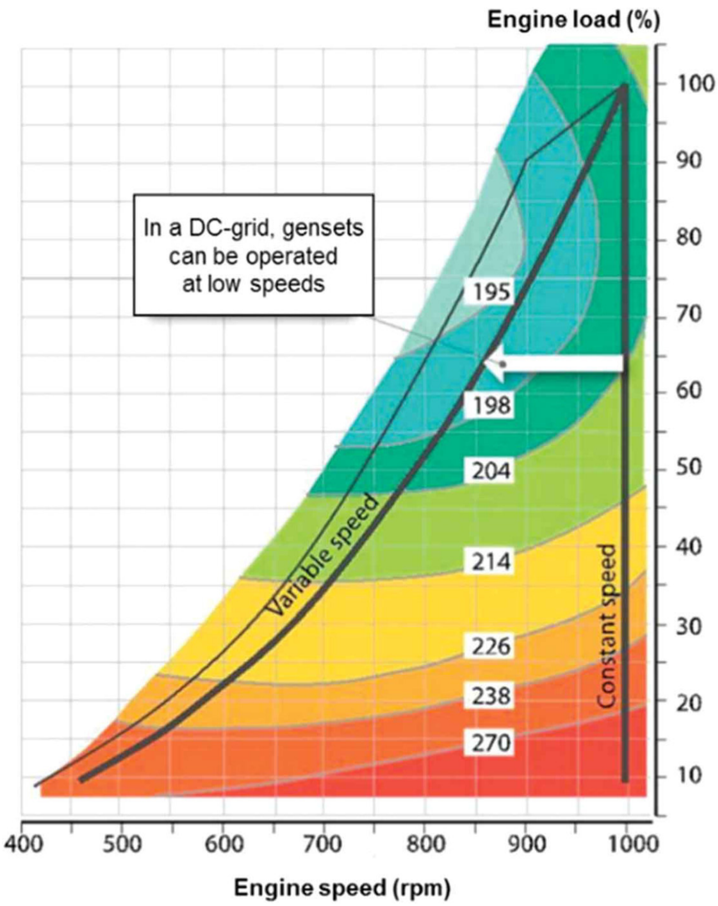

Figure 5.1: Sfc diagram [15]

5.2. Emissions

During diesel engine operation two types of emissions are expelled. Air pollutants and greenhouse gasses. Air pollutants among others can lead to eutrophication, acidification and have a negative effect on respiratory systems. Greenhouse gasses contribute to global warming. Table 5.1 shows the emissions expelled by a diesel engine and whether they are polluting, a greenhouse gas or both. The amount of each emission expelled can depend on multiple factors. However, they are all related to the fuel consumption [5] [16]. Other factors that influence the amount and type of emissions are the fuel type, local engine temperatures and incomplete combustion. The increase of emissions due to the latter two requires very specific modelling of a diesel generator or engine.

	Polluting	Greenhouse gas
H_2O		x
O_2		
N_2		
CO_2		x
SO_x	x	
NO_x	x	x
C	x	x
PM	x	x

Table 5.1: Diesel emission properties

The pollutant emission ratio (per) shows how much pollutant emissions are expelled per unit of fuel. This is shown in Equation 5.5. specific pollutant emission (spe) can be used to express how much pollutants are expelled per unit power. This is shown in Equation 5.6.

$$per = \frac{\dot{m}_{pe}}{\dot{m}_f} \tag{5.5}$$

$$spe = \frac{\dot{m}_{pe}}{P_B} = per \cdot sfc \tag{5.6}$$

Predicting the amount of CO_2 and SO_x expelled is not complicated, if the fuel consumption and quality are known. However, for predicting the emission of NO_x, soot and PM highly complex models and engine characteristics are required. This is caused by the fact that the formation of these emissions is not solely depending on fuel quality, but also on engine conditions. E.g. NO_x formation depends on temperature, where soot formation depends among others on engine loading. These are not solely depending on how much fuel is used, but on how the engine is used. This research will cover the emissions of CO_2 and SO_x. This can be supplemented with information with regards to the emission of NO_x, C and PM [5]. However, during transient behaviour the NO_x and PM emissions can increase by an order of 1 or 2 [17]. Therefore, non continuous loading of diesel engines can have a detrimental effect on the environmental impact of the engine.

5.3. Electric generator and motor

To turn mechanical energy into electrical energy, electric generators are used. With a few exceptions 3-phase AC (a)synchronous generators are used for this. The difference between an AC and DC generator in terms of geometry is how the electrical circuit is connected to the rotor.

5.3.1. Working principle of electric generator

The working principle of an electric generator is based on Faraday's law. This states, that whenever a coil is moved with respect to a magnetic flux that is fixed in space a voltage is induced over its terminals. The value of this voltage (E) is shown in Equation 5.7. The flux density (B) is given in Tesla, the active length of the conductor (l) is given in meters and the relative speed of the conductor (v) is given in meters per second.

$$E = B \cdot l \cdot v \tag{5.7}$$

The electric generator consists of a rotor and a stator. The rotor contains coils and the stator contains north and south poles. These are either established by using permanent magnets (in which case it's called a permanent magnet generator) or by using coils which are powered by an electric current and therefore create a magnetic field. In Figure 5.2 and Figure 5.3 a basic AC and DC generator are shown. In reality the stator will consist of multiple poles and the rotor will contain multiple coils. The rotor is attached to the engine shaft. Due to rotation by the engine a voltage is induced over the rotor terminals. This voltage is used to power the grid [18].

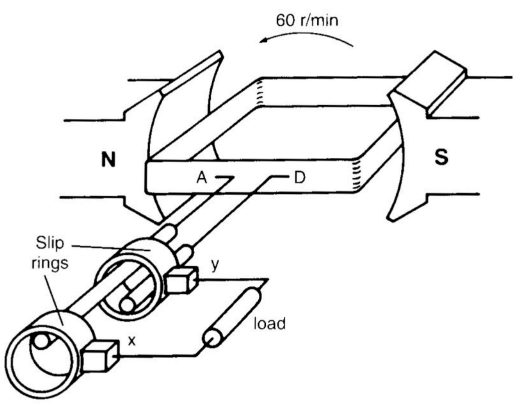

Figure 5.2: AC generator with slip rings

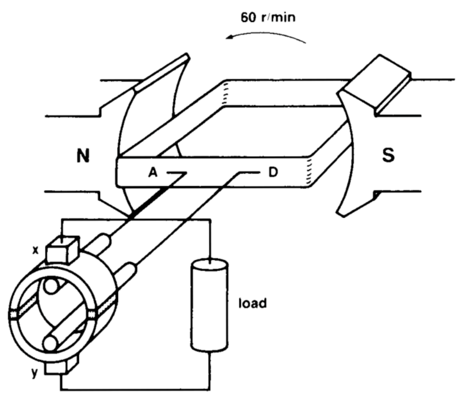

Figure 5.3: DC generator with commutator

Voltage induction in both the AC and DC generator is identical. By default the current direction in the coil will alter direction twice every rotation due to the coil orientation. Therefore if the connection between the grid and the rotor does not change an alternating current is induced in the grid. If one wants to induce a DC current in the grid a commutator should be used instead of slip rings. In a commutator the terminals switch connection to the grid twice every rotation, therefore transferring a DC load to the grid. The connection in the commutator is made by means of commutator brushes. However, these limit the power output and need more maintenance than AC generators. Therefore DC generators are not often used in maritime applications [5] [18].

5.3.2. Working principle of electric motor

The working principle of an AC motor is the inversed working principle of an AC generator. Introducing an AC current on the rotor coil while in a magnetic field will induce a Lorentz force on the rotor, which will lead to rotor rotation. The magnitude of the Lorentz force acting on the rotor can be determined with Equation 5.8. The Lorentz force is always perpendicular to the plane in which the magnetic field and current are directed.

$$F_L = I \cdot l \cdot B \tag{5.8}$$

5.4. Generator speed

Two types of generators can be identified with regards to speed. Constant speed and variable speed generators. A constant speed generator operates at a fixed speed and can alter the power by adjusting torque. A variable speed generator can alter power by adjusting torque and by switching between a discrete set of engine speeds. This increases generator efficiency when running below nominal power compared to a constant speed. E.g. when running the generator from Figure 5.1 at any power, the sfc decreases for lower engine speeds. A variable speed generator benefits from this principle. Variable speed generators are especially useful when dealing with an operational profile where a substantial part of the time low loads are present [15].

Besides, variable generators increase time between overhauls by around 20% which saves money and time. However, a disadvantage of the variable speed units is that additional electrical components and increased programming leads to a cost increase of around 15%. Also variable units emit less noise. As an example, mtu-solutions [19] compared a variable and constant speed generator at 20% power output. For this power output the variable speed generator operates at decreased torque and speed, whereas the constant speed generator operates at decreased torque. This resulted in 6 dB(A) less noise in case of the variable speed generator.

Since Feadship is mostly interested in using variable speed generators in the future, these will be used in the power plant model.

5.5. Prime mover modelling in power plant model

A substantial share of the emissions associated with a diesel engine are not directly related to general operational parameters, like fuel flow or engine speed. In order to predict the amount of especially NO_x, C and PM emitted, extensive diesel modelling is required. Besides, the diesel models used should be calibrated for a specific diesel engine. This will reduce the applicability of the research. Therefore certain emissions will not quantitatively be taken into account during this research. However, due to the aforementioned increase of NO_x and PM emissions during transient behaviour, it can be beneficial to limit the amount of transient loads on a diesel engine. The prime mover will be a zero order model, which will give insight into torque and fuel consumption from a mathematical point of view. Dynamics of a turbocharger will not be included. This will improve the research quality with regards to the implementation and dynamics of ESS' and leave more room for contingency studies, like the implementation of alternative prime movers. This is discussed in section 5.6.

5.6. Alternative prime movers

Diesel engines are characterized by their flexibility and reliability. Compared to other prime movers, like gas turbines, they have shorter start up times and higher ramp rates [20]. From an operability point of view this makes them suited for delivering fluctuating power. However, in order to achieve the global sustainability goals, (a share of) diesel generators will be replaced by sustainable prime movers, like fuel cells. In terms of start and ramp rates the future prime movers are inferior compared to present day diesel engines. Therefore, current power fluctuations that are within the operational limits of a diesel engine, might not be within the limits of future prime movers. This introduces an additional advantage of using an ESS for load levelling.

6
Energy storage systems

Energy storage systems (ESS) are used for temporarily storing energy in order to improve system performance. This can be done in terms of peak power output, fuel efficiency or for load shifting. In this chapter will be determined which ESS could be suitable for application in yachts. Based on the power consumption, which is discussed in chapter 3, several ESS will be selected for further research.

6.1. Available Energy Storage Systems

ESS can be categorized in four types: mechanical, electrical, chemical and electrochemical [21]. Numerous systems are available, however, energy storage is all about trade-offs. One cannot install a system with both the highest power and the highest energy density simultaneously [22]. This is a reason why installing two different ESS could lead to a higher system efficiency, than installing one.

Criteria on which an ESS can be chosen from a functionality perspective, can be, among others, the power density, energy density, system efficiency and the cycling times. When actually implementing an ESS additional criteria such as investment costs, life cycle costs, construction constraints and CO_2 emissions should be considered [23]. Figure 6.1 and Figure 6.2 show the energy and power density range of available ESS [24].

The energy densities of lithium-ion batteries and fuel cells are high compared to the other ESS'. Currently the main disadvantage of lithium-ion is the short life time, where fuel cells have limited power density and ramping capabilities.

6.2. Energy storage system of choice

Which ESS is preferred depends on the type of loads that it will be exposed to. The absolute power and energy that are required to level a peak and the ratio between these two can be used to determine which ESS is suited. The required power of an ESS should be at least equal to the maximum amplitude of the load to be levelled. The required energy is equal to the integrated value of the power. As shown in Figure 6.3 the ratio between power and energy for a given power peak is determined by the peak shape and duration. A peak with a relatively low surface area and duration requires a power dense ESS. A peak with a high surface area and duration requires an energy dense ESS. Please note that the peak amplitude is proportional with both the ESS power and energy capacity and therefore has no effect on the power/energy-ratio. This means the power amplitude does not influence which ESS is suitable. The dimensioning of the system is determined by the absolute values of power and energy.

In Table 6.1 the properties of the aforementioned power peaks are shown. The P/E-ratio gives the relation between the power and energy density which an ESS should have to level these peaks. These ratios are included in Figure 6.1 and Figure 6.2 as additional graphs. From the graph can be seen that wave loads require a more power dense ESS, whereas hotel loads require a more energy dense ESS. Moving up along the peak graphs to the top right corner gives devices with a decreasing gravimetric and volumetric density for the given P/E-ratio. For yachts it is important to minimize the space that is required for components. Both the supercapacitor and SMES are able to deliver the same P/E-ratio. However, the supercapacitor can be up to 3 orders of magnitude smaller for the same performance.

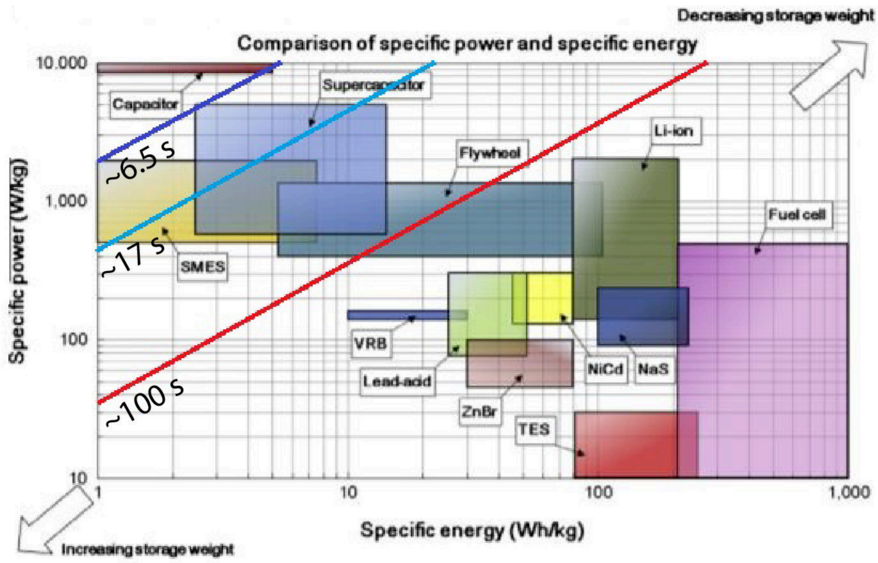

Figure 6.1: Power and energy density for various ESS (hotel = red; calm seas = light blue; MARIN towing test = dark blue) [24]

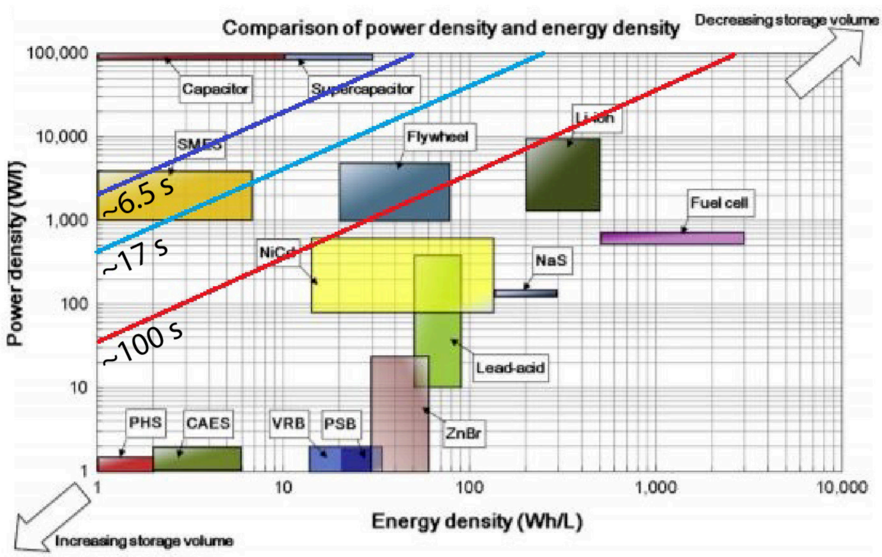

Figure 6.2: Power and energy density for various ESS (hotel = red; calm seas = light blue; MARIN towing test = dark blue) [24]

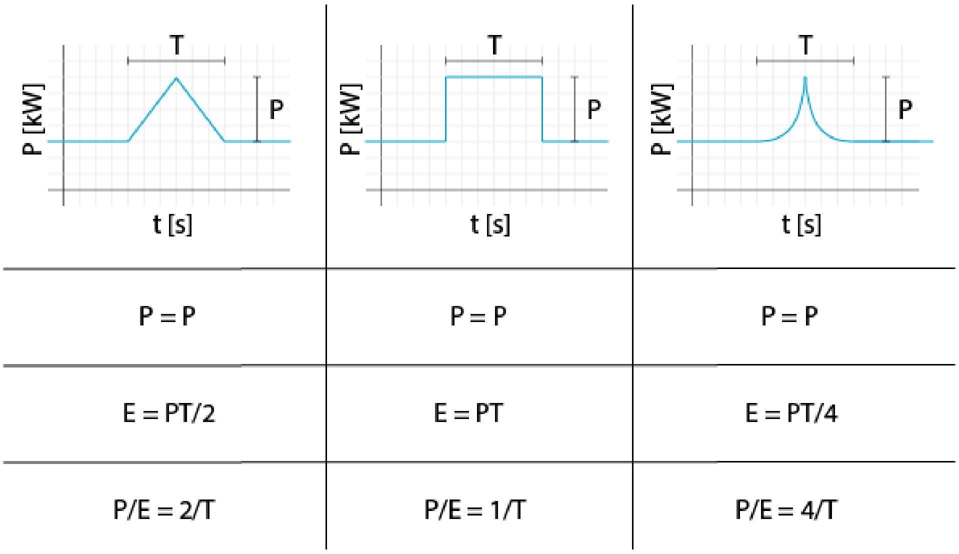

Figure 6.3: Power and energy ratio for different peak shapes.

Therefore the capacitor, supercapacitor and flywheel will be considered in this research. SMES will not be considered. The peaks induced by sailing in calm seas have a small amplitude compared to the main engine power at around 1%. Levelling these peaks will have a marginal influence on fuel savings. The hotel load peaks require an ESS that is very close to the current lithium-ion battery and therefore it will possibly lead to marginal profits to install an additional ESS to level these loads. The power peaks that will be considered in this research involve the peaks of sailing in highers sea states. These peaks require an ESS of a very different nature than the currently installed lithium-ion batteries. Besides, the ramp rates that are required for supplying power can be too high for future prime movers.

Table 6.1: Peak properties

	Peak shape coefficient [-]	Duration [s]	P/E-ratio [-]
Hotel (Figure 3.3)	1	100	36
Waves (Figure 3.2)	2	17	424
Waves (Figure 3.5)	2	6.5	1107

7
Lithium-ion batteries

In this chapter batteries as ESS will be discussed. section 7.1 discusses the physical working principle of batteries; subsection 7.2.2 discusses battery degradation with regards to the operational properties; subsection 7.2.1 discusses the properties that are important with regards to storing energy.

7.1. Battery working principles

Batteries are an electrochemical ESS. Energy is stored by means of a chemical reaction. A battery cell consists of a cathode and anode which are placed in an electrolyte. In case of lithium-ion batteries the cathode is constructed of a lithium-ion oxide and the anode of graphitic carbon. Energy is stored by means of a chemical reaction. When charging the battery, redox reactions occur at both the cathode and anode. During discharge, when chemical energy is converted to electrical energy, electrons flow from the negatively charged carbon to the positively charged lithium-ion.

7.2. Battery energy storing properties

In this section the operational characteristics of lithium-ion batteries will be discussed.

7.2.1. Energy and power density of current batteries

Currently the Akasol, Corvus Blue Whale and Corvus Dolphin batteries are in use on Feadships. In terms of gravimetric density these batteries are corresponding with the data shown in Figure 6.1. In some cases, the volumetric density of these batteries is worse than Figure 6.2 suggests. In the main research the batteries that will be used should be matched with batteries that are actually suited for marine applications.

7.2.2. Battery degradation

Lithium-ion batteries are subjected to degradation, in which the energy capacity decreases during its lifetime. Two types of aging can be identified, calendar and cycle aging. Calendar aging depends on time (t), state of charge (SoC; σ) and cell temperature (T). Cycle aging depends on the amount of cycles performed (n), the corresponding depth of discharge (DoD; δ), state of charge and cell temperature. This relation is shown in Equation 7.1. This relation leads to linear degradation results. However, Xu et al. [25] state that this is an oversimplified model, since it does not match with degradation experiments. During initial stages the battery degradation rate is higher than during later stages. When the battery approaches its end of life (EoL) battery degradation increases again. By convention EoL is reached, when the capacity drops below 80% of its original value. This is illustrated in Figure 7.1. Since battery degradation is varying throughout the operational life, the age itself is an influencing factor too.

$$f_d(t,\delta,\sigma,T_c) = f_t(t,\overline{\sigma},\overline{T}_c) + \sum_i^N n_i f_c(\delta_i,\sigma_i,T_{c,i}) \tag{7.1}$$

In Figure 7.2 battery degradation test data is shown. This data illustrates that the degradation rate is positively correlated with 1) storage temperature, 2) SoC and 3) DoD.

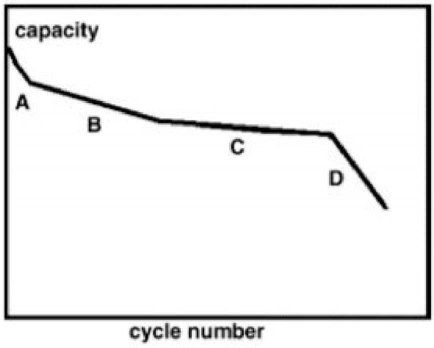

Figure 7.1: General lithium-ion capacity [25]

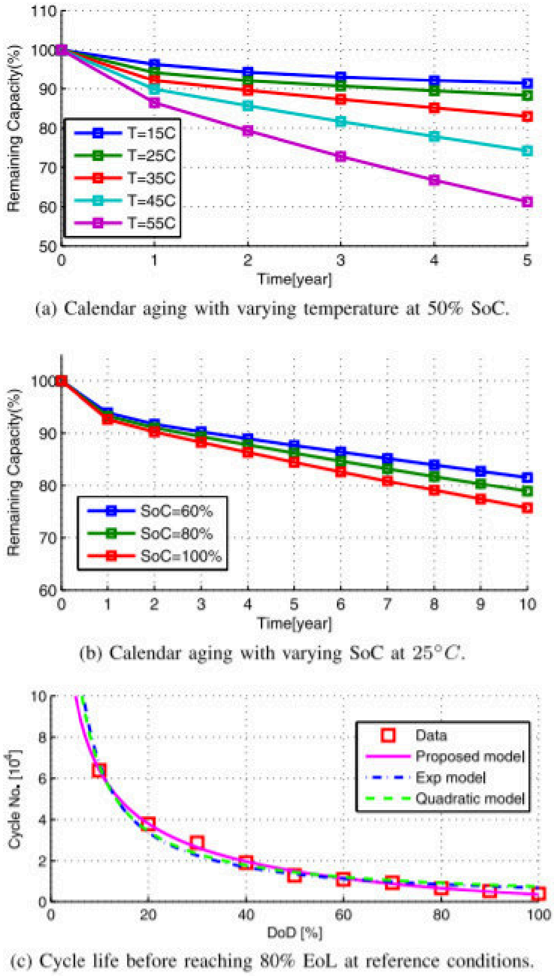

Figure 7.2: Battery degradation test data [25]

7.3. Modelling of lithium-ion batteries

During the dynamic analysis the SoC and DoD of batteries should be tracked in order to assess the battery degradation. Keeping both as low as possible will be beneficial. The storage temperature will not be included in the dynamic model, since this depends on the ship design itself.

8
Flywheels

In this chapter flywheels as ESS will be discussed. In section 8.1 the available types of flywheels and the physical working principles are discussed; section 8.2 discusses the properties that are important with regards to storing energy.

8.1. Flywheel types and working principles

Flywheels are a mechanical type of ESS. They store energy in the form of rotating bodies. The main component of the system is an axle on which rings, disks or discrete weights are mounted. By means of using an electric motor or generator (and no mechanical coupling) energy is stored by accelerating the mass. Energy can be distracted by decelerating the spinning mass. The amount of stored energy is depending on the flywheel moment of inertia (I) and angular velocity (ω), as shown in Equation 8.1. The power rating of flywheels is depending on the sizing of power electronics and the installed motor or generator [23][26][27].

$$E_{rot} = \frac{1}{2} I \omega^2 \tag{8.1}$$

The moment of inertia and the angular velocity can be increased, to increase the stored energy capacity. However, increasing the rpm can lead to a decrease in moment of inertia due to structural constraints [23]. That is why two different types of flywheels are available on the market today. The conventional metal low speed systems (energy density of ~5 Wh/kg; rotational speed of ~5-6$*10^3$ rpm) and high speed composite systems (energy density of ~100 Wh/kg; rotational speed of ~$1*10^5$ rpm). Due to the structural constraints the former have a low energy density and higher standby losses. Typically they are used for short term and medium to high load applications. The high strength, which makes them able to withstand up to 100000 rpm, and low weight of composites give more freedom in designing a system with regards to specific energy and power. However, the costs can be much higher [24][27].

8.2. Flywheel energy storing properties

In this section the operational characteristics of flywheels will be discussed.

8.2.1. Efficiency and losses

When flywheels are in rotation, energy is constantly dissipating. This makes the efficiency of flywheels highly time dependent. In short term applications the efficiency can reach values as high as ~95%, but the self discharge losses are significant. Ranging from 3% to 20% per hour. Eventually the flywheel energy storage efficiency will converge to 0% (in the order of days).

Energy dissipation during flywheel energy storage occurs by means of windage, bearing and conversion losses. The self discharge losses consist of the windage and bearing losses. Minimizing the windage losses can be done by using a vacuum housing or by using a gas mixture with a lower kinetic viscosity than air. The bearing losses can be minimized by using low friction or magnetic bearings.

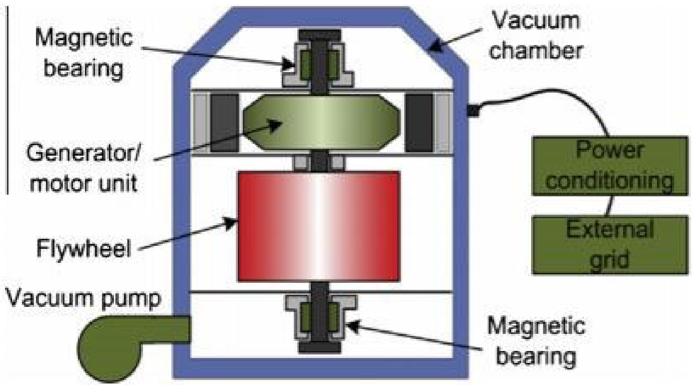

Figure 8.1: Flywheel system [24]

Among others the use of high temperature superconductor bearings is being researched. More research is performed in the field of new flywheel materials in order to obtain higher rotational speeds [24][26][23].

8.2.2. Lifetime and response time

Flywheels are one of the most durable ESS currently available. They have a functional lifetime of over 15 years and tens to over hundreds of thousands storing cycles. This makes flywheels suitable for storing energy at higher frequency e.g. multiple cycles a day. In terms of response time flywheels have a comparable performance as Li-ion batteries, SMES and (super)capacitors, which is in the order of magnitude of milliseconds [24].

8.3. Safety and comfort of flywheel energy storage

When considering flywheel energy storage some practical cases should be considered. Safety being one of the most important, due to several accidents with flywheels in the past. Rotor cracks due to circumferential stresses, rotor shaft defects due to torsional stresses, composite flywheel rotor cracking or softening due to overheating and external hazards, like, earthquakes, excitations or penetrations are named as the general failure roots by Esche [28]. To increase safety the housing and bunkering of the system should be sufficient, in case of failure this prevents rotor fragments from harming people or destroying structures. In reality a flywheel in a yacht might have a lower gravimetric and volumetric density than chapter 6 suggests. Additionally high speed composite flywheels are mainly used for grid stability purposes. In this case a bunker can be created by placing the flywheel underground and these flywheels will not be exposed to imposed displacements. In case of placing such a flywheel in a moving yacht, design compromises are inevitable. This means state of the art grid stability flywheels cannot be used to their full potential on board of yachts.

A high degree of comfort is essential on board of yachts. In terms of noise, flywheels perform well. The flywheel rotates in a vacuum and is magnetically supported, therefore no physical connection between the rotor and housing exists. The noise that is associated with high speed composite flywheels comes from the electrical converters [28].

9

Capacitors and Supercapacitors

In this chapter (super)capacitors as ESS will be discussed. In section 9.1 the available types of (super)capacitors and the physical working principles are discussed; section 9.2 discusses the properties that are important with regards to storing energy.

9.1. Capacitor types and working principles

While capacitors and supercapacitors show similarities in name and physics they rely on different storage mechanics.

9.1.1. Capacitors

Capacitors store energy in an electrostatic way. They consist of two electrical conductors (metal), seperated by a layer of insulator (ceramic, glass or plastic). When a capacitor is connected to an electrical circuit a potential difference is created between the conductors. The potential difference will store energy in the form of an electrostatic field, as shown in Figure 9.1. Subsequently, when the voltage in the circuit drops the charged capacitor can act as a voltage source. This makes capacitors ideal for power quality stability and they are not often used in stationary ESS applications. Compared to batteries, capacitors charge faster, have a much higher power density, but a much lower energy density [27][24][23].

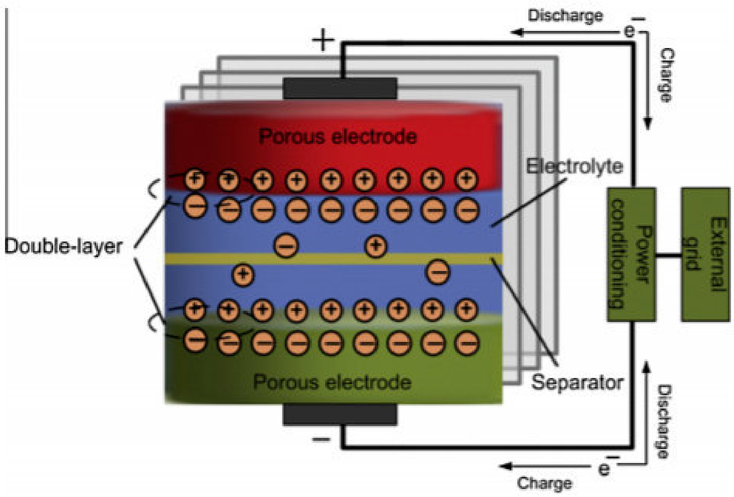

Figure 9.1: Capacitor [24]

The energy storage capacity of a capacitor is the capacitance (C), which is depending on the (smallest) conductor surface area (A), the inductor separation (d), the permittivity of the dielectric material

(ε_r) and the vacuum permittivity (ε_0), as shown in Equation 9.1 in which the vacuum permittivity is by definition 1 [29][30].

$$C = \frac{\varepsilon_r * \varepsilon_0 * A}{d} \tag{9.1}$$

9.1.2. Supercapacitors

Supercapacitors bridge the gap between batteries and capacitors, by storing energy in an electrochemical way. Compared to a capacitor a supercapacitor has a much higher conductor surface area and a much lower *effective* inductor separation. In supercapacitors the electrodes are made from a metal with a porous coating (often carbon). This leads to a high inductor surface. Since a supercapacitor works differently than a capacitor, the conductor separation is not about the distance between the positive and negative electrode, but the distance between the positively and negatively charged particles. This particle layer forms on both electrode boundaries, whereas in a conventional capacitor this layer exists between both electrodes. This makes the distance between the particle layers for a supercapacitor much smaller than for a conventional one, as shown in Figure 9.2. Therefore, supercapacitors are often referred to as electrochemical double layer capacitors (EDLCs).

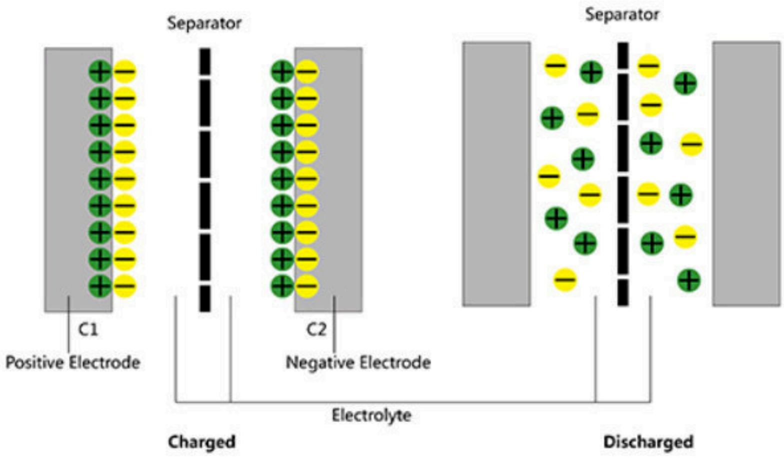

Figure 9.2: Supercapacitor [31]

Despite the differences, Equation 9.1 too applies to supercapacitors. The increased A and decreased d give supercapacitors a much higher capacitance than capacitors. The capacitance of supercapacitors can range from $1{*}10^{-3}$ to $1{*}10^{5}$ F, whereas even kilofarads are off bounds for capacitors. This gives supercapacitors higher energy densities than capacitors, but it also slows down the charge and discharge process leading to a decreased power density. Compared to batteries, supercapacitors charge faster, have a higher power density, but a lower energy density [29][30][31].

9.2. Capacitor and supercapacitor energy storing properties

In this section the operational characteristics of capacitors and supercapacitors will be discussed.

9.2.1. Efficiency and losses

Capacitor cycle efficiency ranges from 60-70% and in some cases exceeds 70%. The daily discharge losses lie around 40%. However, cases have been reported of 50% discharge losses in 15 minutes. In terms of cycle efficiency supercapacitors surpass capacitors with efficiencies ranging from 84 to 97%. The daily discharge losses have been noted to be 5-40%. Because of the discharge losses both capacitors and supercapacitors are mainly useful in short term applications [24].

9.2.2. Lifetime and response time

In contrary to batteries, no chemical reactions take place in (super)capacitors. The charge and discharge of energy is a purely physical matter, by the movement of ions and electrons in the electrolyte and conductors. Therefore, wear and tear in (super)capacitors is slim to none. The lifetime of a capacitor can exceed 50000 cycles. For a supercapacitor this can even exceed 100000 cycles. Both ESS have superior response time in the order of milliseconds. Depending on the type of capacitor the charging time is between $\sim 1\ \mu s$ and ~ 1 ms, whereas a supercapacitor takes ~ 1 s. This makes capacitors suitable for filtering AC line ripple. They can be used for power management, while supercapacitors are more suitable for energy management, due to their higher energy density [24][30][31].

10

ESS trade-offs

Selecting an ESS is all about trade-offs. Each type has its own strengths and weaknesses. In this chapter a comparison of lithium-ion batteries, flywheels, capacitors and supercapacitors will be given.

10.1. Overview of ESS' power storing properties

Based on chapter 6 till chapter 9 the following things stand out. Firstly, capacitors and supercapacitors offer big advantages in terms of power density over both batteries and flywheels. Therefore, these are most suitable for levelling peaks of short durations. In terms of power density flywheels and batteries have comparable properties. Secondly, batteries offer the highest energy density. The other systems in descending order of energy density are flywheels, supercapacitors and capacitors. Due to the fact that lithium-ion batteries are superior in terms of energy density compared to flywheels, these will be preferred in many cases. This is illustrated in Figure 6.1 and Figure 6.2. For only a small range of peak durations the flywheel turns out to be the most suitable, e.g. when levelling hotel peaks in Figure 6.1, if minimizing the gravimetric density is the goal. Thirdly, the round trip efficiency of batteries, flywheels and supercapacitors is similar at around 95%. Capacitors perform below par with a mere 60-70%. Please note that the round trip efficiency of the additional ESS' is subjected to storage duration. Therefore these ESS are useful in the seconds to hours range. When storing energy for days it is preferred to use batteries or the diesel generators.

Table 10.1: ESS properties (these values correspond to Figure 6.1 and Figure 6.2) [24]

	Batteries	Flywheels	Capacitors	Supercapacitors
Power density [W/kg]	150-2000	400-1500	10^5, 10^7	10000
Power density [W/L]	1500-10000	1000-5000	100000+	100000+
Energy density [Wh/kg]	75-200	5-100	0.05-5	0.05-15
Energy density [Wh/L]	150-500	20-80	0.05-10	10-30
Round trip efficiency [%]	90-97	90-95	60-70	>95

10.2. Operational and design considerations for ESS'

Apart from power storing properties the ESS' have practical advantages and disadvantages. An important trade-off regards the lifetime. All ESS' considered outperform the lithium-ion batteries. The former, can reach up to 20000 cycles, whereas capacitor lifetime can exceed 50000 cycles and flywheel and supercapacitor lifetime can exceed 100000 cycles. Besides, lithium-ion batteries degrade by each cycle, whereas the capacity of flywheels, supercapacitors and capacitors is not influenced by age. A 100 kWh flywheel energy storage, will still store 100 kWh after 100000 cycles after 10 years. Depending on the amount of fluctuations in the operational profile, this could be an important criterion.

An important concern when installing flywheels is safety. Flywheels require a robust casing and should be bunkered away in order to prevent fatalities or structural damage in case of failure. Besides, higher safety factors, than strictly required, are used by some manufactureres to prevent failure at all. Lastly, high speed magnetically beared flyhweels are primarily used in land applications. Using a flywheel on board of a ship that imposes movements, will inevitably lead to design compromises.

10.3. ESS' to be evaluated in main research

The flywheel and supercapacitor perform sufficient to excellent in power density, energy density, round trip efficiency and cycle times. In continuation of this research, supercapacitors, lithium-ion batteries and flywheels will be evaluated. However, due to the safety concerns that flywheels are associated with, priority will be given to the former two. Due to the low efficiency of capacitors these will not be evaluated in the main research.

11
Conclusion

This chapter will discuss the key takeaways of this literature review. Besides, it will cover the knowledge gaps and the main and sub research questions.

11.1. Project goal

The main goal of this research is to create a more sustainable maritime industry by contributing to the global sustainability goals. As stated in chapter 1 this will be done by finding new ways to minimize the amount of harmful emissions emitted. Complementing the use of batteries with an additional energy storage system (ESS) could lower the emissions that are introduced by an ICE or can facilitate the use of new prime movers, like fuel cells. The power plant in which the added value of an additional ESS will be assessed, is the diesel electric set up. As described in chapter 2 this is a versatile power supplier for ships with a varying operational profile or a high hotel load. In chapter 3, ways of setting up the power demand of a typical yacht are described. Determining the power demand by means of modelling separate power consumers is not feasible, within this research. Time traces of actual Feadships or model tests can be used to gain insight in the power consumption. In chapter 4, different energy management strategies are discussed. The Equivalent Consumption Minimization Strategy is found to be the most effective strategy, while still being not too complex in terms of mathematics and computational complexity. In chapter 5 the working principle of diesel generators and the corresponding emissions are discussed. The research will mainly focus on the emission of CO_2 and SO_x. Predicting the amount of NO_x, C and PM requires complicated engine models. These need to be calibrated for specific generators, which lowers the robustness of this research. Due to an increased amount of NO_x, C and PM expelled during transience, it will be beneficial to level the load demand for the generators. Besides, the variable and constant speed generator are compared. The variable speed generator turns out to be most suited in terms of fuel consumption for low load operational profiles. Lastly, the working principle of AC permanent magnet motors and generators is described. This knowledge can be used in modelling the power plant. In chapter 6, an overview of the available types of ESS is given. The power fluctuations due to hotel consumers, sailing in calm seas and sailing in higher sea states are evaluated. Subsequently it is determined that flywheels, capacitors and supercapacitors are selected for further evaluation in chapter 8 and chapter 9. chapter 7 gives insight into lithium-ion batteries as an ESS. Both flywheels and (super)caps perform well in terms of operational lifetime and response time. However, flywheels come with some safety concerns. In order to guarantee safety, the flywheel should be bunkered and an increased safety factor should be used during design in order to prevent failures. Due to the limited round trip efficiency and energy density of capacitors, it is in chapter 10 decided to exclude these from the main research. Flywheels and supercapacitors are deemed to have potential in increasing the power plant efficiency and operability, and limiting the emissions. Therefore these will be part of the comparison in the main research. However, due to safety concerns of flywheels these will be given low priority, compared to supercapacitors.

11.2. Research questions and knowledge gaps

Based on the project goal the following research question will be answered:

How do alternative energy storage systems compare for levelling wave induced power fluctuations on board of diesel electric yachts for lowering emissions and facilitating sustainable prime movers?

Energy storage systems form an important link between the power demand and supply in a yacht. On the demand side, an increase in wave height will lead to an increase in both the static and dynamic ship resistance. Therefore waves are a prominent factor in the propulsive power demand. On the supply side, the prime mover has the biggest influence on power generation. Diesel engines under fluctuating loads will be less efficient. Fuel cells under fluctuating loads might not be able to provide in the required power demand at all. Subsequently, the optimal ESS configuration is highly dependent on the properties of power demand and supply. This presents the following sub questions:

1. *What is the influence of sailing in waves on the required propulsive power?*

2. *What are the operational performances of (alternative) prime movers and by which limits are they restricted?*

Modelling the propulsive power plant provides insight to the power supply-demand interaction. Key components for such a model are the prime mover (diesel generators, fuel cells), the selected ESS' (lithium-ion batteries, flywheels and supercapacitors), the ship propeller and the energy management system. This presents the following sub questions:

3. *How can prime movers, ESS' and a propulsor be represented in a power plant model?*

4. *How can the (A-)ECMS be implemented in the power plant model?*

This model can be used to evaluate the operation of ESS configurations. The practical value, however, will be in determining the (near) optimal ESS configuration for a given power demand and supply. First, optimal should be defined. This means criteria should be set up for evaluation of an ESS configuration. Examples of these criteria are system efficiency, volume and weight. The assessment criteria should be among the model output. Based on this output an optimization method can be determined, to find the optimal ESS configuration. This can either be done manually or by using dedicated optimization programming. This presents the following sub questions:

5. *Which criteria are used to compare ESS configurations?*

6. *Which method can be used to determine the optimal ESS configuration?*

Answering the aformentioned sub questions will result in an ESS evaluation tool for Feadships. This tool can be used to compare power plant concepts in an early design stage. If the optimization is automated, this tool will provide a (near) optimal ESS configuration. This configuration can consist of lithium-ion batteries (of varying c-rates), flywheels and/or supercapacitors.

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