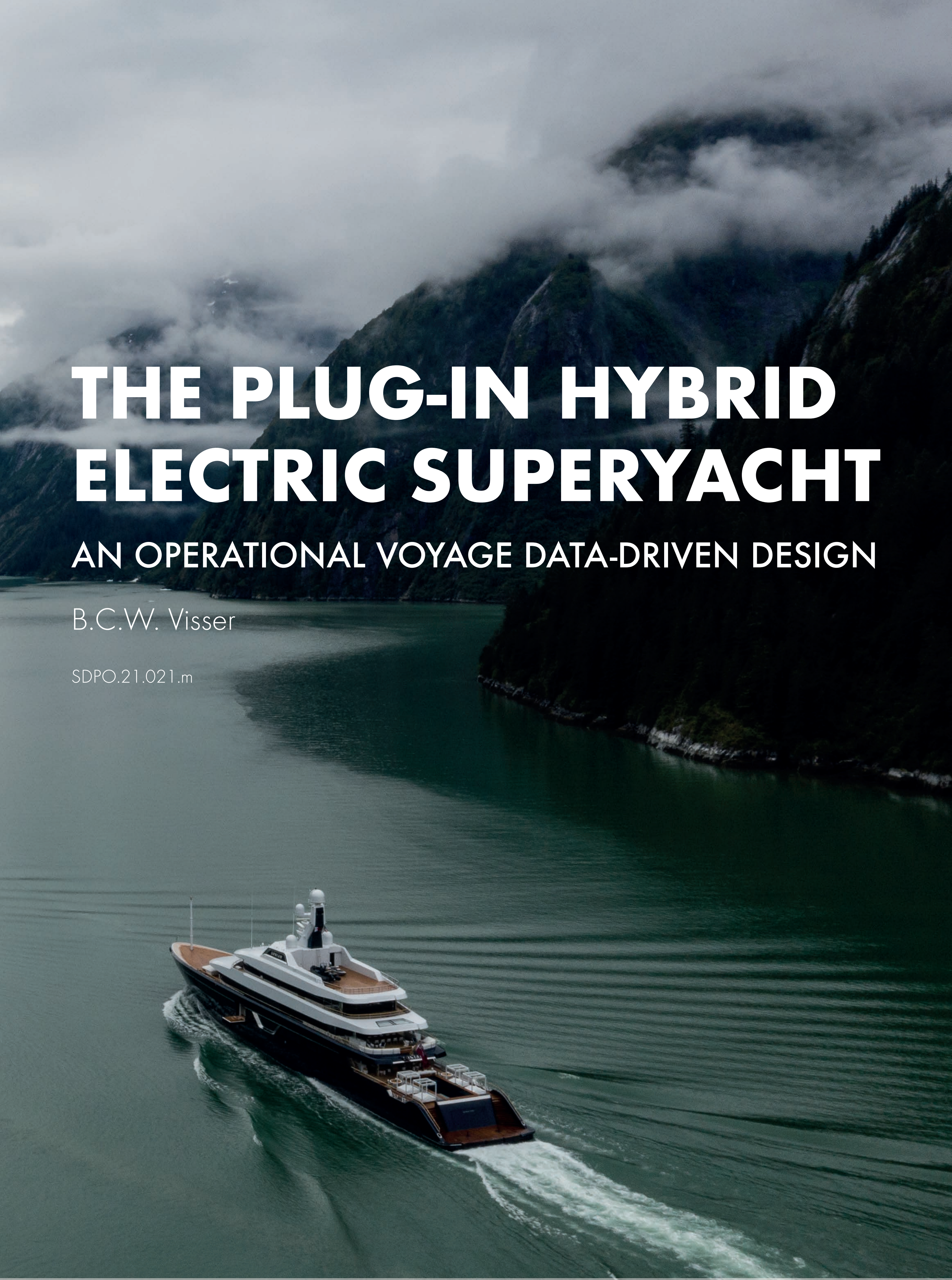
THE PLUG-IN HYBRID ELECTRIC SUPERYACHT

AN OPERATIONAL VOYAGE DATA-DRIVEN DESIGN

B.C.W. Visser

SDPO.21.021.m



TU Delft

DE VOOGT
NAVAL ARCHITECTS

FEADSHIP
ROYAL DUTCH SHIPYARDS

The Plug-in Hybrid Electric Superyacht

An operational voyage data-driven design

by

B.C.W. Visser

to obtain the degree of Master of Science

at the Delft University of Technology,

to be defended publicly on Monday August 16, 2021 at 14:00.

Student number:	4374592	
Project number:	SDPO.21.021.m	
Project duration:	November 15, 2020 – August 16, 2021	
Thesis committee:	Prof. Ir. J.J. Hopman,	TU Delft, chairman and academic supervisor
	Dr. A.A. Kana,	TU Delft, committee
	Dr. Ir. P. de Vos,	TU Delft, committee
	Ing. B. Jongepier,	De Voogt Naval Architects, company supervisor

TU Delft

Abstract

The yachting industry is committed to contribute its part to reduce environmentally harmful greenhouse gas emissions. This rapid shift in the industry is induced by regulations, but also by the pursuit of social acceptance of the industry. However, combining sustainability with pure luxury turns out to be challenging. An all-electric yacht has been deemed feasible but too limited in operation, however, the increased use of emerging battery technologies in a yacht is an opportunity. The solution proposed in this study is the plug-in hybrid electric concept. This propulsion system, compared to a conventional diesel-electric propulsion system, uses an enlarged battery system capable of being plugged into the local power grid in parallel with generators that are decreased in size. The intrinsic philosophy of the concept is that the batteries can be recharged via shore power in marinas, providing a more sustainable source of energy. In this study, three different yacht sizes are investigated, each with three different all-electric autonomy versions.

Two analyses are performed to gain insight into the feasibility of the concept. A statistical operational voyage data analysis is performed to obtain a design speed and all-electric autonomy for the concept. The statistics indicated that the concept only had to be designed for a single design speed, based on a Froude to waterline length relation. The all-electric autonomy for the concept needs to be designed to be in the range of 2 to 3% of the full range capability to have a significant impact. In addition, a questionnaire was sent to marinas worldwide to obtain the actual shore power values available. By subtracting the hotel load from these available shore power values, the available charging powers are obtained. Since shore power varies in different regions of the world and hotel loads vary by yacht size, there is a wide variation in expected feasibility.

Regression analyses are performed to obtain the different design parameters for the equipment of this concept. Therefore, datasets of lithium-ion batteries and high-speed diesel generator sets are examined. Additionally, design parameters of the concept specific required auxiliary equipment are determined.

In the design phase, the total available compensation weight is first determined. Therefore, three methods of weight compensation are introduced based on decreasing the size of the generators, optimising tank usage, and adding displacement. This results in a maximum weight that can be added by the concept that fits within the margins of the early stage design. Of this added weight, the three different all-electric autonomy versions of the concept all take up a different share (0.0%/2.5%/5.0%). The generators are scaled to a single required design cruise speed, which is derived from the statistical analysis. Using the regression design parameters, parametric designs are created in accordance with the set weight limit per version. Design characteristics such as mass, volume, installed generator power, installed battery capacity, and resulting autonomy are determined. The resulting autonomies all fit the design range of the statistical analysis.

The generated effects of these concept versions are determined via a comparison with a diesel-electric benchmark on four aspects: Design, Sustainability, Comfort and Operation. The impact on design is examined by determining the additional weight and volume absorbed. It is found that the impact falls within early stage design margins due to the reduced size of the generators and is therefore minimised. To determine the impact on sustainability, a life cycle analysis is performed. This is an important decision factor in considering this concept. Although the results are highly dependent on the input values determined, the maximum theoretical impacts are significant. Another important decision factor is the impact on comfort. Since comfort largely overlaps with pure luxury and an owner often does not want to compromise on luxury, it is desired that the concept only causes for comfort benefits. The performed qualitative analysis showed that this is the case when considering noise and vibration, exhaust signature, and operational freedom. Finally, the impact on the operation itself. It is expected that a customer would not want to compromise on operational capability, so this impact should be minimised. Although the power output of the generators is reduced, the impact is small but not zero. This is because the concept uses the power characteristics of the installed battery modules.

In order to test the actual operational capability, a test cruise is carried out along the French and Italian coasts. This visualises the battery's state of charge during operation. It was shown that the concept can already be implemented in small yachts and in the future also in medium-sized yachts. Large yachts are excluded because their estimated charging times in the different shore power scenarios are too long.

Preface

Ever since I became affiliated with the maritime industry, I have been intrigued by the sustainability threats it is facing. Using my knowledge of marine technology to contribute to a solution is something that challenges me. The plug-in hybrid electric concept presented in this study is a product of this ambition. The result is this master's thesis, which is required to receive my master's degree in Marine Technology at Delft University of Technology.

I am thankful for the support I received from the TU Delft during my studies. Hans Hopman, I would like to thank you for your academic guidance and help throughout the entire graduation process. During our regular progress meetings, you always asked me critical questions that steered me in the right direction when I was stuck. Your critical and academic aptitude was enormously valuable for the final outcome of this thesis.

Next, I am very grateful for the opportunity that De Voogt Naval Architects has given me to study such a relevant and practical concept. I would like to express a special word of gratitude to Bram Jongepier for his endless support and daily guidance. Thank you for your inexhaustible knowledge, critical feedback, and great enthusiasm for the subject and my findings. Even in these difficult Covid times, it was possible to have a pleasant collaboration. Your enthusiasm is just contagious. Through your guidance and interesting discussions, I have always been able to have the right knowledge at my disposal accompanied by the right view of mind.

A big thank you to everyone who helped me during my thesis, colleagues at De Voogt, employees from other companies, and of course the graduate interns at De Voogt. Your knowledge, insights, and help were always at hand, and luckily there was always time for a coffee break. These short meetings were always a welcome source of distraction in stressful moments.

Additionally, I am also very relieved and happy to have graduated from the TU Delft. Ever since I was a little boy, I always said that I wanted to graduate from this university. That moment has now come after seven joyful years of study, including nine hard months of graduation. During those years, I have met a lot of lovely people and certainly made lifelong friendships. The memories I have are fantastic and I will always carry them with me. But now it is time to leave the university behind and take the next step. The memories will certainly continue to be made, but now with a master's diploma in hand.

Finally, I would like to thank my family, friends, and loving girlfriend. Thank you for listening to my (silly) boat stories. Without your endless love and support, I would not be the man I am today or enjoyed my studies as much as I did. Thank you for everything.

Bobby Cornelis Willem Visser
The Hague, August 2021

Contents

Nomenclature

List of Acronyms

AC	Alternating Current
AER	All-Electric Range
AET	All-Electric Time
AIS	Automatic Identification System
BC	Boundary Condition
BMS	Battery Management System
CD	Charge-Depleting mode
CDF	Cumulative Density Function
CS	Charge-Sustaining mode
DC	Direct Current
DD	Diesel-Direct
DE	Diesel-Electric
DMA	Distillate Marine grade A
DoD	Depth-of-Discharge
DVNA	De Voogt Naval Architects
ECA	Emission Control Area
EEA	European Environment Agency
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Index
EOL	End Of Life
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
GT	Gross Tonnage
GWP	Global Warming Potential
HVAC	Heat, Ventilation and Air Conditioning
IEA	International Energy Agency
IMO	International Maritime Organisation
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
Li-ions	Lithium-ions

LIB	Lithium-ion battery
LMO	Lithium manganese oxide
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MY	Motor yacht
NCA	Lithium nickel cobalt aluminium oxide
NECA	Nitrogen oxide Emission Control Area
NMC	Lithium nickel manganese cobalt oxide
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particle matter
PMS	Power Management System
PSSA	Particular Sensitive Sea Area
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SoC	State-of-Charge
SoH	State-of-Health
SP	Shore Power
SSC	Special Service Craft
SY	Sailing yacht
TTP	Tank-to-Propeller
TTW	Tank-to-Wake
UF	Utility Factor
UN	United Nations
VS	Volume-share
WRF	Water Revolution Foundation
WS	Weight-share
WTP	Well-to-Propeller
WTT	Well-to-Tank
WTW	Well-to-Wake
YETI	Yacht Environmental Transparency Index

List of Symbols

Δ	Displacement
$\dot{E}$	Energy flow
η	Efficiency
η_{dg}	Diesel generator set efficiency
η_{EM}	Electric-mechanical efficiency
η_{em}	Electric motor efficiency

η_{fc}	Frequency converter efficiency
η_{fi}	Frequency inverter efficiency
η_{MM}	Mechanical-mechanical efficiency
η_{swbd}	Switchboard efficiency
ρ	Density
C_A	Admiralty coefficient
d	Distance
E	Energy
f	Frequency
F_n	Froude Number
g	Gravimetric acceleration
I	Current
L_{wl}	Length waterline
P	Power
T	Temperature
t	Time
t_b	Time at berth
U	Voltage
v_s	Ship speed

List of Units

%	Percentage
A	Amperage
hr	Hours
Hz	Hertz
kg	Kilograms
kts	Knots
kW	Kilowatt
kWe	Electric kilowatt
kWh	Kilowatt-hour
m	Metres
m^2	Square metres
m^3	Cubic metres
nm	Nautical mile
t	Metric tonnes
V	Volt
W	Watts
Wh	Watt-hour

List of Figures

List of Tables

I

Introduction & Concept Exploration

1 Introduction

In a world where harmful emissions are being reduced in every possible way, even a ship's power plant is subject to innovation. Electrification in all transport industries has its impact on the engine room of a yacht. Diesel-electric propulsion is becoming the standard in yacht propulsion and marks a shift towards a more sustainable industry. It represents a departure from the established mechanical propulsion systems that run on fossil fuels, while maintaining comfort levels. This study proposes a new propulsion concept for the yachting industry and aims to provide a proof of concept. The new concept extends the electrification while considering the impact on design, sustainability, comfort and operation.

This rapid shift in the maritime industry is induced by regulations from the International Maritime Organisation (IMO) with its vision to phase out greenhouse gas (GHG) emissions as soon as possible, forcing the industry to reduce its fossil fuel consumption and develop alternative propulsion systems. The IMO based its urgency on the conclusions of the third GHG study conducted in 2014 [51], with an update in the fourth GHG study conducted in 2020 [12]. This found that the shipping industry as a whole emits an average of 1036 million tonnes $CO_2 - eq$ [1] per year. With the global anthropogenic emissions averaging at 36745 million tonnes, the maritime industry is thus responsible for 2.8% of the global GHG emissions.

To ensure that the maritime industry is consistent with the Paris Agreement temperature targets set by the United Nations [55], regulations are being strengthened towards a 50% reduction in GHG emissions by 2050 compared to 2008 levels. Ultimately, IMO wants the industry to fully decarbonize by the end of this century. With this goal in mind, the IMO has set three different levels of ambition that will lead to regulation of emissions in the design phase of a ship, but also in its operation [32]. An example of this is the sulphur cap that came into force in 2020, which reduces GHG emissions from shipping by using much lighter distillates. The author of DNV-GL created a model projecting the effects of full decarbonization for the industry and concluded that to completely phase out these GHG emissions, fossil fuel use must be cut out completely [8]. This confronts the maritime industry with the exploration of alternative propulsion systems and power plant options, accompanied by a switch to alternative energy sources. In particular, the increasing supply of renewable energy to the power grid creates the potential for renewable energy stored in on-board batteries to become a key technology [26].

Accounting for 0.01% of the total global emissions (4.9% of maritime emissions), the yachting industry has an obligation to do its part [51]. Reducing their share while meeting the high demands of their customers is an ambitious challenge. Customers' demands are usually not limited to the desire to reduce harmful emissions, but also consist of an increase in comfort or the desire to install the latest technology. Legislation and customer demands play an important role, but are accompanied by public opinion, which can be decisive. As Feadship's head of design, Ronno Schouten, explained, "Yachts will not be socially accepted in the future if they do not become more sustainable." Therefore, in parallel with the maritime industry as a whole, battery technology is being considered as a solution for a yacht's power plant, due to its silent and local zero-emission characteristic supported by rapid development and extended implementation in other industries.

[1] Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the three main GHGs. Their combined contribution is presented in a single value based on Global Warming Potential (GWP): CO_2-equivalent ($CO_2 - eq$).

The leading industry in powertrain electrification is the automotive industry, as the electric vehicle (EV) market is steadily growing and taking an ever-increasing market share from conventional vehicles. All major automakers, led by Tesla, have at least one all-electric model in their lineup. Consultancy firms such as, but not limited to, Deloitte [62] and Bloomberg [38], predict that the share of all new EVs sold will increase to 10% by 2025, with a possible expansion to 25% in the following five years. This ongoing development in various industries is improving battery technology and increasing its energy density in terms of both weight and volume. This plays into the hands of the maritime (i.e. yachting) industry, where energy demand is high but available space and weight are limited.

Electric propulsion in the maritime industry has been around since the early 1900s. Over the centuries it has been widely used on various types of ships, mainly naval vessels and passenger ships, as explained by Moreno Sáiz and Pigazo López [40]. The option of going fully electric on a superyacht is deemed feasible by Akershoek. However, he concluded that an all-electric yacht will have some limitations compared to a regular superyacht. It is in fact limited in customer specifications in terms of range, speed, and charging time, mainly caused by a poor charging infrastructure [3].

An intermediate option that has the potential to disregard these limitations, yet still increase sustainability and comfort, is a plug-in hybrid electric superyacht. It is a concept designed to increase a superyacht's shore bound electrical energy demand by displacing part of the distance in complete silence using shore power stored in the batteries. In this way, fossil fuel consumption and corresponding local emissions will decrease, contributing to a more sustainable industry, while maintaining (or increasing) performance and comfort. This concept leverages current developments in the battery and renewable energy industries and has also been proven in the automotive industry [38, 62]. However, it has not yet been implemented at this scale in the maritime industry.

De Voogt Naval Architects (DVNA), a subsidiary of Feadship, is a naval architect company active in the superyacht market that wants to make its portfolio more sustainable by expanding it with a plug-in hybrid concept. They have already conducted a preliminary study on the feasibility of a 45m plug-in hybrid superyacht. Yet little is known about the characteristics and implications of such a concept applied in a superyacht. Therefore, they concluded that an in-depth scientific study is needed to determine the characteristics and impact of the new concept and take the next step to make the industry more sustainable.

1.1. The plug-in hybrid electric concept

The propulsion system proposed in this study is a new electric concept with a plug-in hybrid power supply. It complements all the advantages that a diesel-electric configuration offers when used in a yacht. The advantages are that noise and vibration levels can be more easily controlled by locating the generators freely in the vessel and mounting them resilient. The elimination of some of the mechanical components results in lower maintenance requirements, thus reducing operating costs. Power transmission via the ship's on-board electrical system provides design freedom in the type of propulsor. Options can broadly include an azimuth or podded propulsor, which eliminates the need for a rudder and has less appendage drag [5, 18]. The disadvantage, however, is that the DE concept comes with higher investment costs and transmission losses. These transmission losses can be as high as 5 to 10%, which can be compensated for by reducing the resistance of the appendages, although this results in a net decrease in efficiency if the design is poor [1]. This concept is favourable when a large non-propulsive electrical load is expected. In a yacht, such large hotel loads are present. The number of generators running can be controlled to operate near peak efficiency at all loads, especially increasing efficiency at lower loads [18, 21]. For more information on this, the reader is referred to the study by Nessink [41].

The studied concept is not yet widely used in the maritime industry, therefore technical information on this concept is lacking. The automotive industry has a comparable technology that is widely used in their plug-in Hybrid Electric Vehicle (PHEV). Therefore, a comparison is made with the automotive industry to obtain relevant information as the working principle of the concept is similar in both industries. A plug-in hybrid electric power plant is considered in the automotive industry as an upgrade of the hybrid electric power plant with increased energy storage capacity, capable of plugging into the local power grid [4, 52]. The concept used in the yachting industry would follow a similar philosophy to that of the automotive industry.

Suppes et al. [52] explains that the plug-in hybrid power plant originated as a transition technology for hydrogen cars towards a hydrogen refuelling infrastructure, but soon found its application in conventional petroleum-powered vehicles. As an upgrade of the hybrid car, this plug-in electric concept has an increased energy storage capacity that enables it to displace part of the fossil fuel distance using only battery power - more than the hybrid concept [63, 65]. The term known in the automotive industry for the displaced distance at a given speed using only stored electrical energy is the All-Electric Range (AER), or the related All-Electric Time (AET). Both are referred to as concept autonomy. This characteristic differs per type, model, and brand and is an important design feature for PHEVs or EVs [4, 46, 58]. This characteristic is therefore also used in the design of a plug-in yacht.

The studied concept has a hybrid electrical power supply. This means that multiple energy sources provide electrical energy in parallel to the on-board power system, either via generators, fuel cells, and/or energy storage systems (ESS) such as batteries [18]. In this study, generators in combination with batteries as ESS are considered. A simplified one-line diagram of the considered concept configuration is shown in Figure 1.1. The size of the generator can potentially be reduced while still meeting the power requirements. The ability to charge the batteries via the local power grid reduces fuel consumption and therefore local emissions. It should be noted that this does not per se reduce global environmental impacts, as the electricity generated may or may not be generated via renewable sources. Only if this is the case can it be concluded that the concept is more sustainable and/or future ready[57].

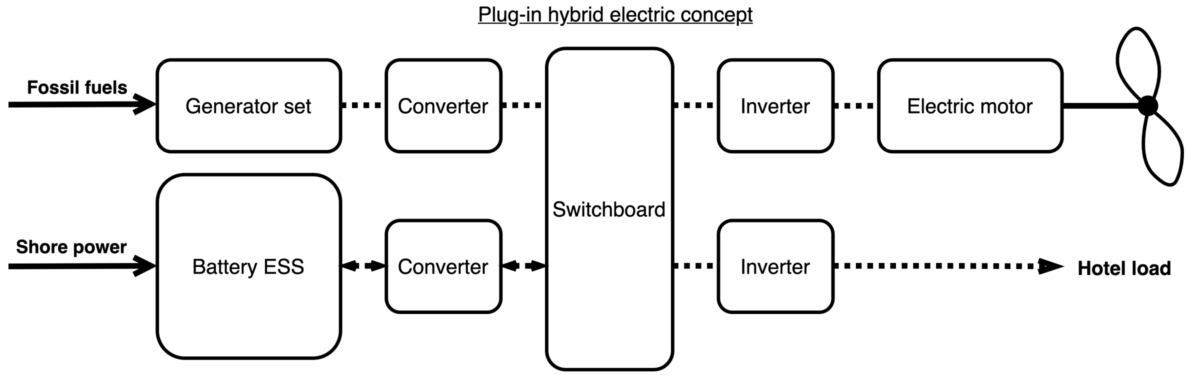


Figure 1.1: A simplified one-line diagram of the plug-in hybrid electric concept proposed configuration.

In the automotive industry, the PHEV has several operating modes installed. The two main modes are the charge-depleting (CD) and the charge-sustaining (CS) modes. The first mode is the all-electric mode, where the battery is used to power the motors and little to no fuel is used. When the battery is depleted, operation continues in CS mode. In this mode, the PHEV is operated like a hybrid, with the generators providing power and keeping the battery level as low as possible [46, 63]. More complex modes, whose implementation in a yacht can be studied, are not considered in this study, but can be very interesting. An example is a mode in which the generators operate to charge the batteries and simultaneously drive the propulsor. This leads to an increased amount of time a yacht can operate in CD mode. This does not lead to a reduction in emissions, but can be used because of regulatory requirements in sailing areas or due to guest requests. For example, if the batteries are depleted and a specific emission control area is to be visited, then a fully charged battery is of great importance. Sailing in a battery charging mode immediately prior to entry can ensure this.

1.2. Potential of the plug-in

Powertrain electrification is a hot topic in the yachting industry as well as in the maritime industry as a whole. In parallel, onshore power generation is becoming increasingly renewable. The combination of the two is the potential that arises for the plug-in concept. It combines both trends by increasing a superyacht's onshore power demand, storing the energy and using it for silent propulsion. As a result, it can replace part of the fossil fuel distance by using only battery power. The corresponding local emissions will decrease, contributing to a more sustainable industry. Note the difference with the principle of "cold ironing", which is known in the maritime industry for the principle of increasing shore-bound electricity demand to replace ships' auxiliary engines when they are in port. This principle is limited only to the use of shore power while in port and not using it for propulsion, whereas sailing on shore power is exactly what the plug-in yacht concept is all about.

The concept has been implemented before in the yachting industry, albeit in much smaller yachts. Companies such as Greenline Yachts [19] and Silent Yachts [50] have developed their hybrid electric yachts, which are up to 80ft long. Both use solar panels and a range extender - a smaller generator - to provide the energy needed for the desired range before recharging. The energy collected from the sun is temporarily stored in lithium-ion batteries. The closest the superyacht industry has come to implementing the plug-in concept in superyachts is with the installed hybrid electric propulsion system on MY Savannah.

1.3. Problem statement

The combination of stringent emission regulations and luxury is challenging, although by displacing part of the distance on shore power stored in batteries, GHG emissions are expected to decrease, while subsequently maintaining or increasing the comfort and performance level of a yacht. Especially when considering the expected future renewable developments of the onshore power grid. The concept is a proven technology in the automotive industry, where the energy demand is significantly lower than in the maritime industry, but little is known about its application in the maritime industry, especially for yachts.

Yachts have a very different operating profile compared to the international merchant fleet, as yachts are typically anchored in a bay, berthed in a marina for extended periods of time, or sailing short distances at low speed. These modes of operation require less energy than sailing cruise modes, plus the longer periods in port have potential. This creates an opportunity for the plug-in concept by powering these (expected) low energy demands via batteries that are charged while berthed in a marina. However, such a concept will only be installed in a yacht if the owner and designer know in advance what impact it will have on design, comfort, and operation. This provides the basis for this research. Accordingly, the problem statement can be summarised in the following main research question:

What is the impact of a plug-in hybrid electric concept on the design and operation of a superyacht, supported by the added value for the owner?

The goal of this study is to provide a proof of concept and describe its effects. This way, designers can adequately inform clients of the pros and cons of this concept when discussing the multiple propulsion system options. Therefore, this research is limited to exploring different versions of the concept and determine the extent of their effects, rather than optimising a single one. A proof of concept is provided when a version of the concept results in a yearly positive effect on sustainability of 10%, while sustaining or increasing her yearly comfort levels and maintaining operational performance levels. This goal is obtained with the use of expert opinion at DVNA.

1.4. Research questions

In order to systematically accomplish this goal, the main research question in this thesis is supported by five sub-questions. These sub-questions are related to the energy demand, storage, and supply of the concept, subsequently resulting in a parametric design and impacts. These questions are answered first before attending the main research question and objective.

1. *What is the expected operational usage of a plug-in hybrid electric superyacht?*
2. *What are the basic design parameters of required equipment on the market?*
3. *What is the available current and future shore power infrastructure?*
4. *What are the resulting parametric designs of the concept?*
5. *What are the characteristic effects of the concept on design, sustainability, comfort, and operation?*

1.5. Document structure

To answer the five questions, this study distinguishes four different phases:

Part I *Introduction & Concept Exploration*

Part II *Technical Analysis*

Part III *Concept Design*

Part IV *Effects & Debrief*

In the first phase, the problem and concept were introduced in the introduction, then their drivers and enablers are explored in Chapter 2. These will be used to determine the design approach for the remainder of this study. This method is explained in Chapter 3.

In the second phase, several technical analyses are performed to determine the input values and design constraints for the design process. First, in Chapter 4, the design benchmark is established with several Feadship yachts and a diesel-electric configuration. Next, in Chapter 5, a statistical analysis of operational voyage data is performed to determine the design speed and range of the concept. To conclude this phase, in Chapter 6, data from a shore power survey is analysed to determine the actual shore power available in marinas.

In the third phase, the determined input values and design constraints are used. The design methodology is first discussed in Chapter 7, then the parametric concept designs are created and presented in Chapter 8.

In the fourth phase, the resulting concept designs are used in combination with the established benchmark to determine the potential impacts in Chapter 9. The four studied impacts are design, sustainability, comfort, and operation. In Chapter 10 a test itinerary is sailed to check the operational performance of the concept versions. These findings and impacts are then used in Chapter 11 to provide an answer to the research question and whether the research objective has been achieved. Chapter 12 discusses the simplifications and research uncertainties, along with recommendations for further research.

2

Concept Exploration

During the concept exploration, the drivers & enablers of the concept are explored. The drivers for DVNA to study this concept are firstly the environmental regulations and secondly the induced modern trends in the industry. Both are discussed in the first two sections of this chapter. Since the enablers of the concept are based on the expected increasing sustainability and usage, preliminary studies on both subjects are conducted in the succeeding two sections.

2.1. Environmental regulations

A key driver for this concept is adherence to existing and future environmental regulations. These provide an important framework for evaluating the plug-in hybrid electric concept as an alternative marine propulsion system. The International Maritime Organisation (IMO) is the international regulatory body for the shipping industry, established by the United Nations (UN), and responsible for the environmental performance of international shipping. At the end of the last century, it adopted several amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) (1973). These amendments focus on the MARPOL Annex VI Prevention of Air Pollution from Ships (1997), which limits emissions of greenhouse gases, NO_x and SO_x. Over the years, environmental problems became more urgent, leading to the Paris Agreement goals of the United Nations [55]. As a result, Marine Environment Protection Committee (MEPC) Session 72 (2018) set an initial strategy with the urgent goal of phasing out GHG emissions as soon as possible this century, leading to further amendments added to the MARPOL Treaty [32]. This includes further implementation of the Energy Efficiency Design Index (EEDI) for new ships; a reduction in CO_2 emissions towards 70% by 2050 compared to 2008 levels, with a reduction of 40% in 2030 as an interim target; GHG emissions to peak as soon as possible, followed by a reduction of 50% from 2008 levels by 2050 [32]. These targets have been set to initiate active research and development in alternative fuels and power plants, as it is expected that the agreed targets cannot be met with the use of fossil fuels. In this way, the industry is forced to innovate and thus this new concept is being considered.

The strategy is supported by regulations that yachts are required to comply with, however most yachts already comply or fall below the thresholds for compliance. There is only one that may limit the cruising experience of guests: the restriction in sailing areas by (future) Emission Control Areas (ECAs), shown in Figure 2.1. These ECAs are enforced in Particularly Sensitive Sea Areas (PSSAs) defined by the IMO. ECAs are areas where restrictions on local NO_x and SO_x emissions are tightened towards Tier III and 0.1% to achieve consecutive NO_x, SO_x and PM emission reductions. Because yachts comply with sulphur ECAs due to their low sulphur fuels, the figure does not distinguish between sulphur ECAs and nitrogen ECAs. As shown, there are currently several areas: The North American Area (since 2012) and the North European Area (since 2021). The North American area includes the Pacific and Atlantic coasts, as well as Caribbean Sea and the coasts of Hawaii. The Northern European area includes the Baltic Sea and North Sea [29–31]. All are typical cruising areas for yachts. Figure 2.1 also shows that possible future ECAs are located in areas where yachts are present, e.g. the Mediterranean Sea. One area not mentioned in this legislation is the Arctic, where HFO use has been banned since 2021 and more are expected [49].

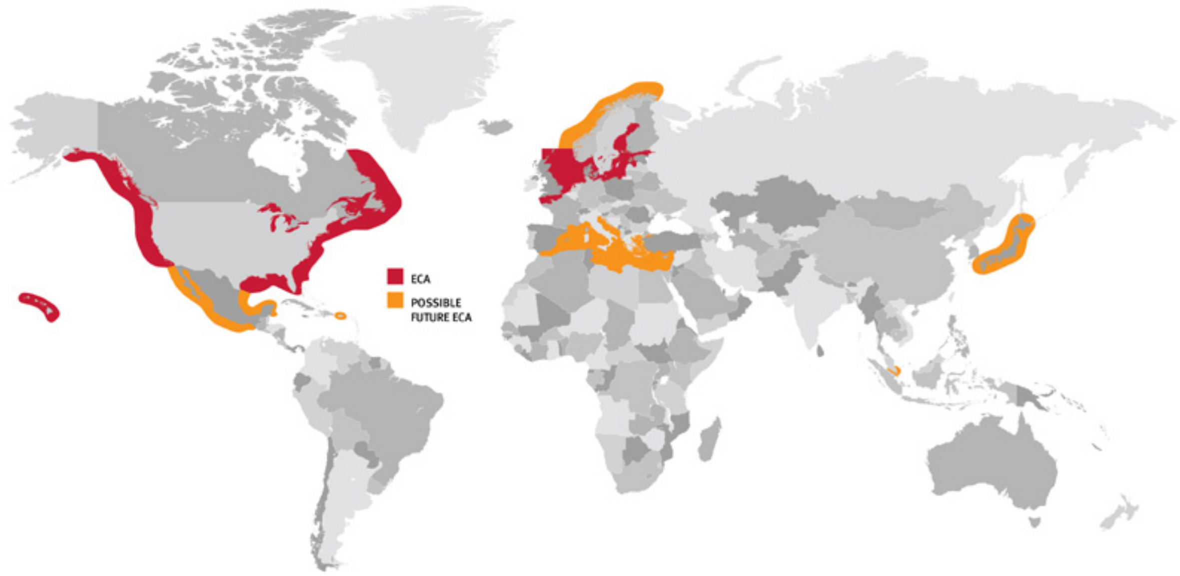


Figure 2.1: Global ECAs as introduced in MARPOL annex VI.

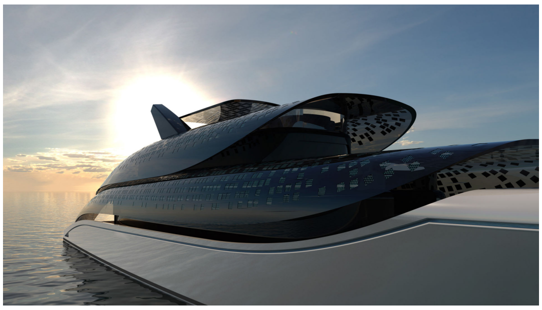
Almost all yachts built by Feadship sail in European waters at least once a year, so they must comply with EU regulations. These are in line with the standards set by the IMO, but allow for local and/or national regulations. One example is Norway. Their government has enacted stricter local emissions regulations to protect UNESCO-protected fjords from local greenhouse gas emissions. By 2026 at the latest, all vessels visiting the Geiranger and Nærøy fjords on Norway's west coast must be emission-free. The regulations also ban the use of scrubbers [9]. Another example, but outside the EU, is the Galapagos Archipelago. This is a PSSA where national legislation is adopted to control the harmful emissions from the yachting industry by issuing permits [64]. It is expected that these areas with stricter national regulations will not be the last. Mainly because nations want to protect their pristine nature and IMO regulation takes a long time before it is actually adopted. Governments can then take the initiative and regulate themselves.

2.2. Modern trends in yachting

The other important driver for this concept is the social acceptance of the yachting industry. All stakeholders are influenced by these societal views and associated actions, creating modern trends in the industry. These trends in the industry are important to make a disruptive change, such as the new plug-in hybrid concept, successful. Therefore, the trends per stakeholder in the yachting industry will be analysed.

To start with DVNA and Feadship as stakeholders. Throughout the industry, designers and builders feel committed to the climate crisis and therefore financially support NGOs [39]. Examples include the Blue Marine Foundation, Safety4Seas, or the philanthropic Water Revolution Foundation (WRF) founded in 2019 by leaders of the yachting industry. All are non-profit organisations with the goal of neutralising the yachting industry's environmental footprint and preserving the world's precious oceans through collaboration and innovation. In addition to supporting and establishing these organisations, superyacht design and engineering firms are steering their new clients in the sustainable direction by designing technically feasible sustainable concept superyachts. Feadship designers have created designs such as Aeon (2009), the first concept with an eco-friendly attitude by running fuel cells on synthetic diesel [13], the groundbreaking Breathe (2010), which reduced her fuel consumption by up to 40

This trend can be observed among superyacht builders, but not only there. In the ever-changing luxury landscape, owners' desires are also trending towards sustainability, as the founder and creative director of Winch Design, Andrew Winch, explains, "Today's superyacht owners are younger and more in tune with the climate crisis around us, and therefore either request or are open to, innovative, sustainable yacht design" [37]. This trend is indicated by the first hybrid-electric Motor Yacht (MY) with an installed MWh battery capacity, launched by Feadship in 2015: MY Savannah (image 2.3a) - based on the aforementioned innovative sustainable concept yacht Breathe. Her pioneering design is aimed at fuel savings of up to 30%, resulting in a signif-



(a) Concept Breathe, 2010 [14].

(b) Concept Escape, 2020 [17].

Figure 2.2: Climate-conscious concept yachts, developed by Feadship.

icant reduction in GHG emissions [15]. Newer Feadships with a sustainable philosophy are MY Najiba, with her lightweight aluminium hull and small engines, or MY Lonian (image 2.3b), which is a smart hybrid with a Direct Current (DC) grid and has optimised battery capacity. Nowadays, a (more or less defined) sustainable approach to design is required by most owners. The extent to which sustainability is actually implemented in the design is, as the senior specialist at De Voogt Naval Architects, Bram Jongepier, explains, "a question of the priority that owners give to sustainability over pure luxury.".[1]

(a) MY Savannah, 2015 [15].

(b) MY Lonian, 2018 [16].

Figure 2.3: Delivered climate-conscious yachts, designed and built by Feadship

It is not only the yachts that are becoming more sustainable. The marinas as their facilitators are also becoming more climate-conscious, or at least a trend can be observed. Innovations such as the Seabin, which acts as a floating trash can that skims the surface of the water by pumping water into it, are becoming more prevalent in the industry [54]. In addition, the EU Parliament advocates for regulating access to ports for the most polluting ships via port state control and is promoting the use of clean on-shore power supply. This is supported by the national power grid increasing its power capacity and becoming increasingly renewable by improving renewable energy production [26]. This has an indirect impact on the sustainability of the recharge, as some marinas currently supply energy via diesel generators ashore to meet high energy demands.

2.3. Sustainability of the recharge

An enabler for this concept is the increasing sustainability of the national power grid, increasing the sustainability of charging in a marina. When a vessel's plug is plugged into the shore power pedestal, it is often automatically assumed that this is the most sustainable way to generate power. No internal combustion engine is started to meet the energy demand, subsequently there is no air or noise pollution, and therefore it must be sustainable, is a common thought. However, the fact that there are no local emissions does not inherently mean that it is more sustainable and/or that there are no harmful greenhouse gas emissions at all. In contrast, Kumar et al. [35] concluded that sometimes connecting to the local power grid is actually more harmful to the environment than running the on-board generators. This conclusion varies by country, as emissions

[1] Conversation with E. Reynolds via email, on 9/12/2020

per kilowatt-hour of electricity generated onshore generally depend on the mix of renewable energy sources supplying the national electricity grid [25].

The International Energy Agency (IEA) [26] is a major data analyst of global energy production and corresponding emissions. Based on their data, they have created a base case expectation for the future development of electricity generation, which is visualised in Figure 2.4. It shows an increase in installed renewable electricity capacity, with the installed capacity of renewable wind and solar surpassing that of coal in 2024. These are expectations in terms of global installed capacity, but similar trends are also expected at a national level [26]. This means that in the future, onshore electrical energy will become increasingly renewable and therefore the connection to the onshore pedestal will become increasingly more sustainable. However, it is important to note that these conclusions are based on general national policies and not on policies in local coastal areas or specific to marinas. Precise information on these areas is design case specific.

The voltage and frequency of the connection varies in different marinas around the world. This problem is solved with a shore power transformer installed on board, which adjusts the frequency and voltage to the required level on board. Ultimately, the charging power is determined by the amperage of the connection. This information is also marina-specific and must be determined.

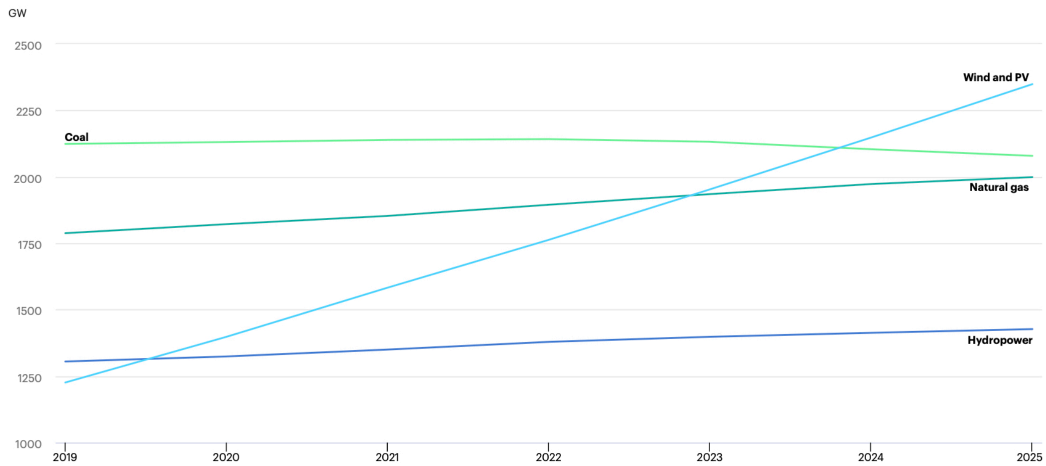


Figure 2.4: Future developments of the total installed electricity grid power capacity by fuel and technology in the period up to 2025 [26].

2.4. Fit for purpose

The introduction suggests that the operational behaviour of superyachts fits the low energy requirements of the concept. The studies of Van Loon and Van Zon [56], Nijhoff [43] and Akershoek [3] are used to confirm this suggestion, albeit in two different ways. Van Loon and Van Zon and Akershoek obtained this information by statistically analysing historical AIS data (Automatic Identification System) of 35 Feadships. The study by Nijhoff [43] is based on a predefined operational profile - an itinerary that is copied from a yacht with a similar expected operation or one that is chosen arbitrarily. The usage is defined using examples from leading superyacht charter companies, taking into account the philosophy of his study. All three studies are reviewed with a focus on geographic and operational usage.

2.4.1. Geographical usage

Superyachts have the advantage of being able to cross seas and oceans, so they move around the globe throughout the year. Their location mostly depends on the seasons, but also on the wishes of the guests. Yachts tend to visit similar locations in Europe and North America, so there are several distinct geographical areas where yachts reside. These are visualised in Figure 2.5. Akershoek [3] distinguishes three different types of generic geographical profiles where yachts reside throughout the year. These areas can already be identified by the dark green colour in Figure2.5 of Van Loon and Van Zon, but are now assigned to a specific operating profile type and subdivided.

1. Type A - Around Europe, but 90% of the time in the North Mediterranean Sea.
2. Type B - Chasing the sun, while relocating between the North Mediterranean Sea and the North American East Coast.
3. Type C - Around the globe, with no specific residing area.

Figure 2.5: Generic geographical profile of superyachts throughout the year. The green areas highlight the areas were yachts tend to reside throughout the year. The dark green areas are the more popular areas, as the Mediterranean and the Caribbean. The typical routes across the ocean are shown with dotted lines. [56]

2.4.2. Operational usage

In order for the concept to meet the required ranges and speeds, insight into operational use is required. This is often based on the expected operational profile, which is mandatory estimated information usually instructed by the owner of the yacht. However, the operational usage is quite different from that of a regular vessel. Where the merchant shipping fleet is obliged to stay in port for as short a time as possible and spend as much time in transit as possible, the yachting fleet is characterised by the opposite. The majority of the time the guests are not on board, in-between stays the crew maintain the yacht and sails the ship to the planned destination. Once there, guests have their desired length of stay while they enjoy water sports, relax on board, and rarely being in transit. They are often berthed in the marina of a city where the elite enjoy their jet-set lifestyle, or anchored in a picturesque bay near a quaint town.

- Akershoek [3] conducted a statistical analysis of the AIS dataset to determine the lengths and speeds of trips between these destinations. The study made no difference in the type of operating profile in terms of trip distances between marinas. The results shown in Figure 2.6 confirm the suggestion that superyachts sail most of the time shorter distances, although he points out that trips of up to $5nm$ are neglected in his analysis. These account for 12.3% of the total number of trips. In addition, he showed conclusions regarding the average annual sailing distance per operational profile type given in Table 2.1. As expected, these show that the average yearly sailed distance increases with the global spread of residing areas.

Table 2.1: Generic data on the operational profile [3].

Type	**Residing area**	**Yearly average sailing distance** [nm]	**Yearly average sailing speed** [kts]
A	Around Europe	7.000	10 – 14
B	Mediterranean & Caribbean	10.000	12 – 14
C	Around the globe	11.500	12 – 16

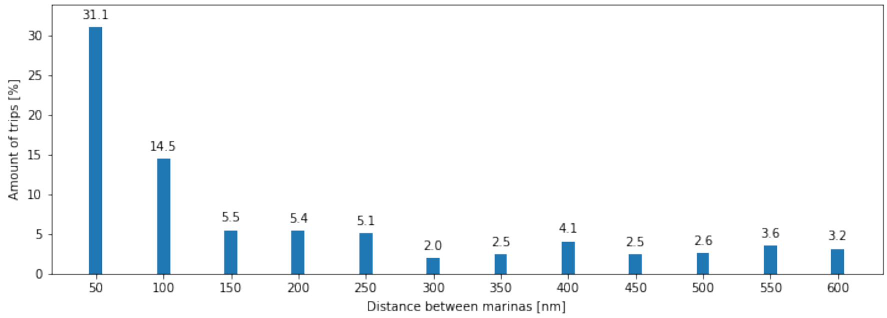


Figure 2.6: Distance travelled between marinas [3].

- The study by Van Loon and Van Zon [56] used the AIS dataset to gain insight into the most often sailed speeds of a yacht. Their first conclusion is that about 90% of the time a yacht is at anchor or moored, it therefore spends only 10% of the time sailing. This highlights the contradictory use of superyachts compared to the merchant fleet. For the remaining 10%, a generic absolute speed distribution is defined, from which Akershoek [3] has made an operational profile-specific distribution. These characteristic speed profiles are included in Appendix A. The data showed a wide operating range, with a high peak at cruising speeds, mostly between 12 and 14 knots. In addition, little time is spent sailing at maximum speeds, and lower speeds are used moderately. Furthermore, Van Loon and Van Zon concluded on the operational profile-type specific yearly average sailing speeds, which are shown in Table 2.1. The increase in the average may be an effect of the more global residence of that operational profile-type, resulting in trips of greater distances sailed at cruising speeds having a larger share of the distribution. This would confirm the suggestion that yachts sail shorter distances at speeds lower than cruising speed when based in the Mediterranean or Caribbean. However, this conclusion does not take into account the increase in cruising speeds with increasing yacht length. A study focused on the waterline length-dependent cruising speeds of yachts is performed by Water Revolution Foundation [61]. A negative linear relationship with the dimensionless Froude number (2.1) is proposed, see Figure 2.7. This is then scaled to the actual cruise speed using the definition of William Froude (2.2).

$$F_n = 0.3385 - 0.0011 \cdot L_{wl} \tag{2.1}$$

$$v_{cruise} = F_n \cdot \sqrt{g \cdot L_{wl}} \tag{2.2}$$

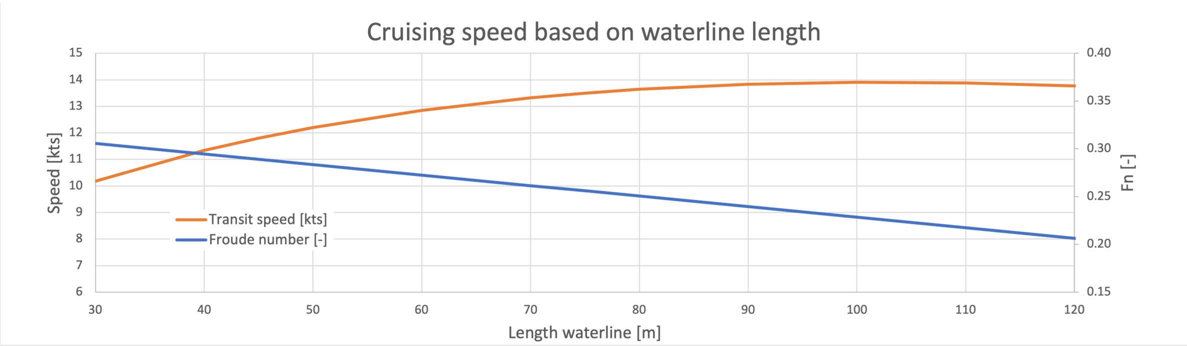


Figure 2.7: The suggested transit speed of a yacht based on length by Water Revolution Foundation [61].

In an in-house study, De Voogt Naval Architects [7] examined the behaviour of superyachts using AIS data. It linked the average speed of a particular voyage to the corresponding distance sailed, which was plotted on a single speed-distance diagram. The result was a minor correlation between the two parameters, indicating a fit for purpose of the proposed concept. However, there are doubts about the validity of the data itself, as the data appear to be linearized between several time stamps.

2.5. Batteries as ESS

The proposed concept uses batteries as ESS, to store shore power. The battery most commonly used by Feadship today is the lithium-ion battery (LIB). This type is also the technology of choice in the automotive industry. Therefore, this section focuses on the characteristics of this type of battery and the regulations regarding its implementation in yachts.

2.5.1. Characteristics

Lithium-ion battery cells are generally considered the most promising battery cell because the main metal, lithium, is widely available, non-toxic, very light, and electropositive [66]. This high electrochemical potential leads to high energy storage potential. This characteristic varies from type to type, as the composition of each type greatly affects the balance between capacity and power. Zubi et al. [66] compared several types of LIBs. Their results are shown in Figure 2.8. They conclude that NCA and NMC battery cells are the most promising. The difference in rated power leads to a different application in the automotive industry. Both are used in EVs, but only the NMC in PHEVs.

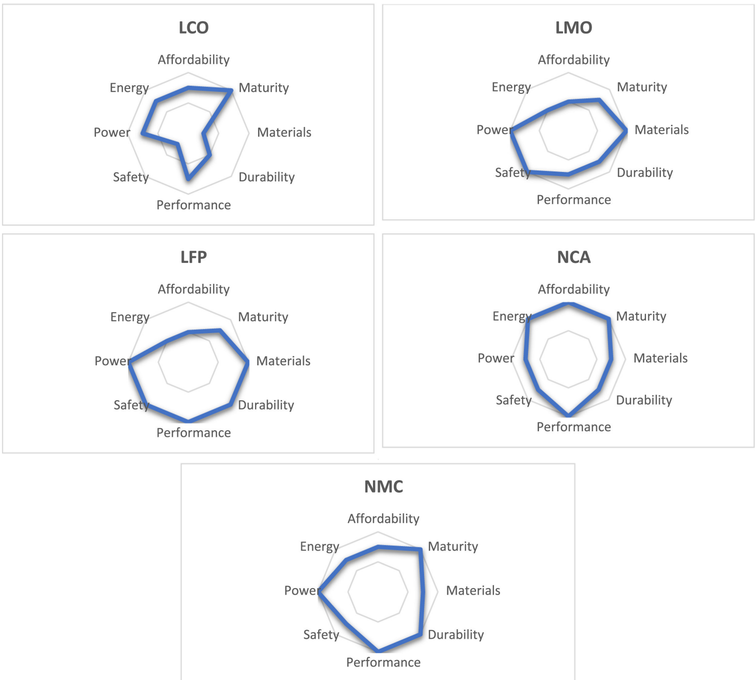


Figure 2.8: A comparison by Zubi et al. [66] of characteristics between commercial LIBs.

The rated power defines the ability of a battery to charge and discharge, limited by the amount of current it can safely deliver. The safety limit is the internal impedance, or resistance, of the battery. In order to charge a battery quickly, a high power rating is required. The rate at which the battery can change from fully charged to fully discharged is the C-rate. Similar to the energy storage potential of LIBs, the power rating is LIB specific. The capacity of a battery is commonly rated at $1C$. This means that a fully charged battery rated at $1Ah$ should provide $1A$ for 1 hour. If the C-rate of a similarly rated battery drops to $0.5C$, it can deliver $0.5A$ for 2 hours, or vice versa.

2.5.2. Battery modules

Battery cells alone are too small to meet the energy or power requirements of a ship, so a fixed number of cells (several hundred) are bundled together to form a module. This module consists of a frame that also protects the cells from external shocks, heat, or vibration. Several of these modules are then bundled together to form a battery pack or rack. This rack contains various control and protection systems, such as a Battery Management System (BMS), cooling system and ventilation system.

The battery modules are controlled by a battery management system (BMS). This system monitors various battery characteristics to ensure safe and optimal use. The monitored characteristics are: Current (I), Voltage

(U), State-of-Charge (SoC), State-of-Health (SoH), and Temperatures (T). When a failure occurs, e.g. thermal runaway of a cell with off-gas emission, the safety systems are activated by the BMS. The SoC is limited by the battery's charging window - the minimum and maximum SoC of the battery. This is referred to as the Depth-of-Discharge (DoD). Overcharging a Li-ion battery reduces the SoH.

To achieve the best SoH and ensure safety, the temperature of the batteries must remain within the limits defined by the manufacturer. There are two ways to cool the battery packs: Forced air cooling and liquid cooling. The type is often specified by the manufacturer, as both have different characteristics. Generally, liquid cooling is more compact, but not always suitable, yet ventilation is already required because of existing off-gasses. Often the regular ventilation system installed on board is sufficient.

2.5.3. Regulation

The new concept must comply with the current safety standards of the classification societies. These have issued strict regulations to mitigate the hazards and safety concerns of battery systems. The two considered classification societies are Lloyd's Register (LR) and, in the yachting industry, the widely accepted Yacht Code of the Red Ensign Group (REG).

The most recent codes of the REG are Part A[2] and Part B[3] of the Large Yacht Code (LY3). Annex 5 considers the application of batteries and is applicable to both codes [48]. LR is the classification society most commonly used by Feadship, so it is considered in this study. In Part 1, Chapter 2, Section 3.6 of the SSC Code of LR the yachts have the denomination Special Service Craft (SSC) Yachts. Therefore, they are classified in the 'Rules and Regulation for the Classification of Special Service Craft'[36]. Recently, a new regulation regarding Hybrid/Hybrid+ vessels has been adopted and added to this code as part 23. At 23.12.2 it states that the electrical energy storage system for hybrid electric power systems must comply with Part 16, Chapter 2, Section 12 'Batteries' of the code.

These regulations set design requirements and set the equipment necessary to cool the batteries, ventilate the rooms, and extinguish any fires. Ventilation of battery rooms is required for two reasons: cooling of the rooms and venting off-gas out of the rooms. If the installed ventilation fails and a fire occurs, the BMS will activate the fire fighting system. Both societies state that the system must be a permanently installed system that can be controlled from a safe position, which is often the deckhouse. They also state that the batteries may not be placed forward of the bulkhead and that new battery modules must be tested first.

[2] Applicable to yachts with a capacity of up to 12 passengers and over 24 metres in length.
[3] Applicable to yachts with a capacity of over 12 passengers and of any length.

3
Design Approach

The concept exploration in the previous chapter provided information on the expected feasibility and fit for purpose of the concept in the industry, but only limited design criteria or parameters were provided. These emerge out of a design philosophy of the concept, combined with available technical market solutions.

3.1. Design philosophy

Behind every newly developed concept is a design philosophy that guides the designer in the right direction for the decisions at hand. This train of thought is consistently followed through in all concept versions. The end result is a concept design that meets the needs. It is already explained that not a single, but multiple versions are designed whose impacts are studied. This is to help designers best inform their clients when considering multiple propulsion options. During this process, you do not want to make rigorous design adjustments to implement a particular option. This results in the following design philosophy of the concept:

To sail part of the fossil fuel distance, using shore power stored in batteries, while minimising the impact on yacht design and corresponding characteristics.

The benchmark propulsion system used to determine the resulting impacts is a diesel-electric configuration.

3.1.1. Design drivers

In order to minimise the impact on the design, it is necessary to know the key drivers that influence the design of the yacht and that are specific to this concept. These are called design drivers and have been identified from a comparison with the automotive industry. They are all related to energy and are grouped in the design driver triangle as shown in Figure 3.1.

The sides of this triangle show the concept properties that have the greatest influence on the two design drivers touched. Charge availability and performance are both constraints within the design, as the designer cannot influence the shore power infrastructure. Consequently, concept autonomy is the only property that can be influenced by the yacht designer. It is expected that the energy demand of a yacht will not change significantly when this concept is implemented, therefore the energy storage is the design driver of the concept.

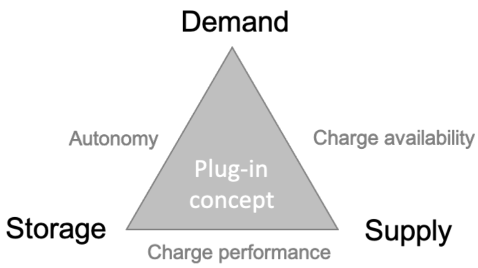


Figure 3.1: The design driver triangle.

3.1.2. Design scope

The on-board energy storage is defined by the installed battery size. Considering the lower energy density of batteries, compared to fossil fuels, additional weight is expected. To meet the design philosophy of minimising the impact on the design, this weight must be compensated. The following three methods are considered:

- Decrease the size of the installed generators.
- Optimise tank usage to operational conditions.
- Increase the displacement with a maximum of 5%.

This 5% is considered as a standard design margin by DVNA in the early design stages. What size these generators are reduced to needs to be studied. The same applies to the effect of optimising tank usage. These subjects will be addressed and determined later in this report.

3.2. Concept versions

In Section 1.3, it is explained that this study aims to provide a proof of concept rather than optimizing a single version. Furthermore, this is a new concept in the yachting industry, so the focus cannot be on a single version. Therefore, multiple versions of the concept are proposed in this section, along with their rationale and a method for testing their effectiveness.

In section 3.1.1, it is stated that the autonomy of the concept is the only property that can be influenced by the designer. Since the owner is the main actor in this study and can only decide what the electric range of his yacht should be, the considered varying parameter is the all-electric range (AER). To what extent the ranges vary will be determined after a usage analysis. The following concept versions are proposed:

- **Short AER**
- **Mid AER**
- **Long AER**

These differences in range lead to differences in the effectiveness of the concept, since the design philosophy is to sail part of the fossil fuel distance on shore power. As this range decreases, so does the effectiveness. To measure the effectiveness of a plug-in hybrid electric concept, one must know the proportion of the distance sailed using battery power only relative to the total distance sailed. In the automotive industry, this ratio is referred to as *"Utility Factor"* (UF). There are several variants of the UF. The most commonly considered UF for assessing general behaviour is the fleet UF, as shown in Equation (3.1) [46, 63].

$$\text{Fleet UF} = \frac{\sum d_{CD}}{\sum d_{total}} \tag{3.1}$$

This equation determines the UF using the cumulative electrical distance divided by the cumulative total displaced distance. Therefore, a large behavioural data set of the entire fleet is required. If the concept has a UF of 1, then all annually sailed distances are powered by battery power. If the concept has a UF of (almost) 0, the distance travelled on battery power is negligible and no benefit is derived from the installed configuration. The UF depends mainly on the installed battery capacity, although many other operational aspects have an influence. Examples of these aspects are the operating profile and the availability of charging.

3.3. Design method

In this section, a design approach is proposed that systematically determines input parameters, creates designs, and checks the resulting impacts to provide an answer to the main research question. This design method is divided into three different consecutive phases of the process:

1. **Input phase**
2. **Design phase**
3. **Impact phase**

The steps are discussed separately and are visualised in Figure 3.2.

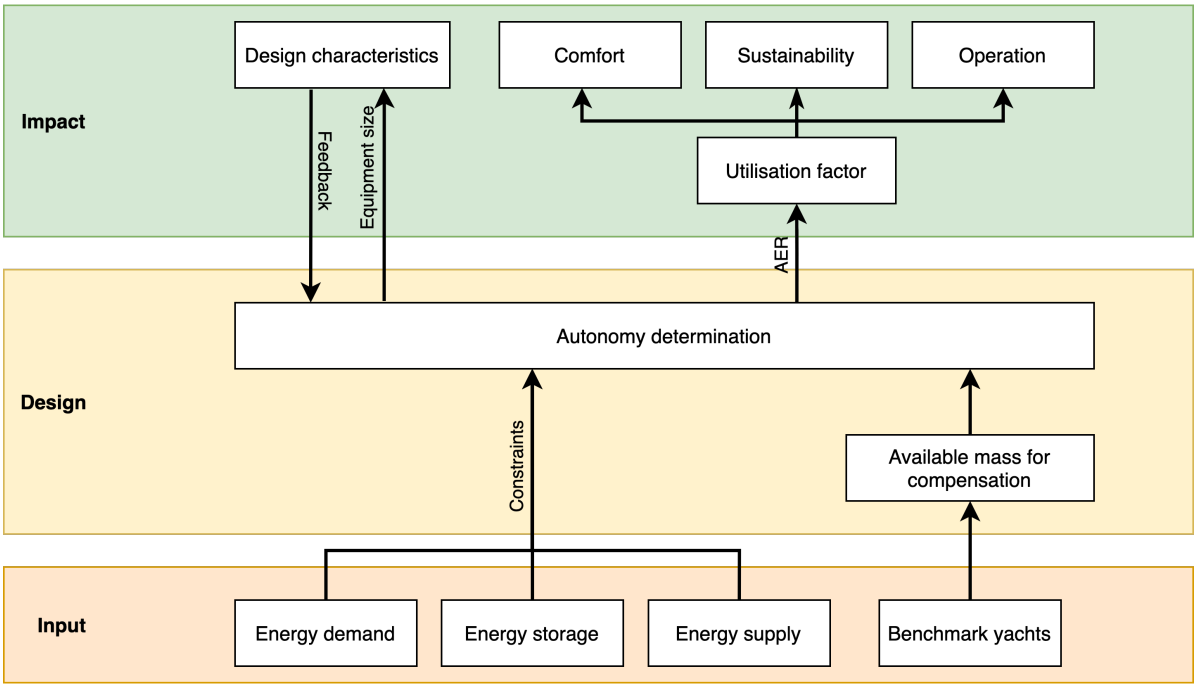


Figure 3.2: A flowchart of the proposed design approach.

3.3.1. Determine input

In the input phase, the three design drivers explained in Section 3.1 are elaborated on - Energy demand, storage, and supply. The resulting design constraints are used in the design phase of the concept. Furthermore, a benchmark is set via several benchmark yachts. Design parameters of these yachts are used in the design phase.

Energy demand The yacht behaviour discussed in Chapter 2 gives a first insight into the operational behaviour of superyachts. An operational analysis provides information on how long a yacht sails and at what speeds. This information is needed to determine the power and energy requirements of the concept. The review showed validated data for medium to long distance trips, but no such conclusion could be drawn for short distance trips. The available AIS data analysis was invalid for trips up to $\leq 5nm$. These accounted for 12.3% of the total trips. This partition did not have a significant influence on the created designs of the reviewed studies, as these studies did not deviate for short-distance trips within the profile, i.e., the step size was $50nm$ in range. However, this may have an impact on the design of the currently studied concept. Therefore, knowledge of this short-trip operational behaviour needs to be improved in two steps: by refining the AIS analysis and then by improving the operational analysis. These topics are addressed in Chapter 5.

1. **Improve AIS analysis**
   DVNA has a large AIS dataset at its disposal, concerning all Feadships. The preceding studies performed by Feadship on behaviour of superyachts are based on this dataset. The problem is that the data is linearised between sampling timestamps. This leads to unrealistic linear behaviour for short trips, while the effect of this linearisation becomes less significant for longer trips. Therefore, the results are assumed to be valid for longer trips. The short trip linearisation will be solved together with employees of DVNA by re-evaluating the data.
2. **Improve operational analysis**
   This improved AIS analysis is then used to improve the operational analysis of the defined yacht profiles. These profiles only provide information on the full range capabilities, while the studied concept splits the operational profile into an all-electric and a diesel-electric part. It is expected that statistics on operational usage will provide the necessary insights for the design. Therefore, operational usage statistics are added to the currently available operational analyses, using the improved AIS data analysis. It is chosen to focus on a single operational profile type, Type B, as the largest proportion of the

Feadship fleet operates according to this profile.[1] The statistical approach will consist of three different analyses: the combined trip scatter analysis, the trip distance analysis, and the trip speed analysis.

- The trip scatter shows each sailed trip as a data point in a range-speed diagram. This scatter is used to assess a possible correlation between the sailed distance and the sailed speeds. This scatter must be constructed with use of the refined AIS-data analysis.
- The trip distance analysis is used to create the trip distance distribution, hence visualising what share of the total sailed trips consists of what distance. The enclosed area of this histogram is the total distance sailed. This trip distribution is used as a yearly average. The expected shape, based on the current available data, is shown as the orange curve in Figure 3.3. This is used to provide a first indication of an effective AER for the different versions of the concept. The effect of the AER for trips longer than the designed AER is still present. This effect is measured with in Section 3.2 determined UF and plotted as the green curve. The area enclosed by this curve describes the total distance sailed fully electric.

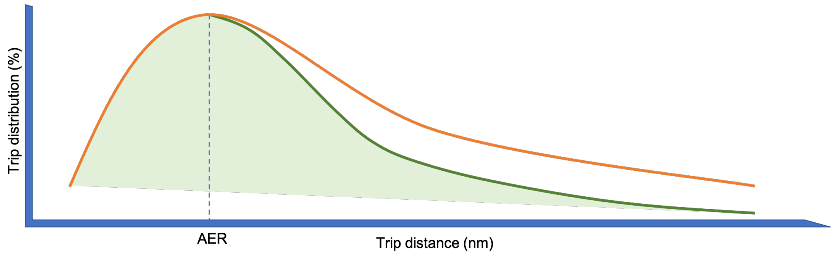


Figure 3.3: An example of the trip distribution.

- The trip speed analysis is used to create the trip speed distribution, hence visualising what share of sailed trips is sailed on what speeds. This is used to indicate at what speed the AER should be determined, resulting in an energy demand of that AER.

The current available data suggest that the majority of the shorter trips are sailed at lower speeds, while the longer trips are sailed at higher transit speeds. This combined with a third power relation between speed and effective power, a significant higher energy demand for longer trip distances is expected. This emphasises the underlying focus for this concept is on shorter distance trips. A visualisation is provided in Figure 3.4.

$$P_E = c_1 \cdot v_s^3 \tag{3.2}$$

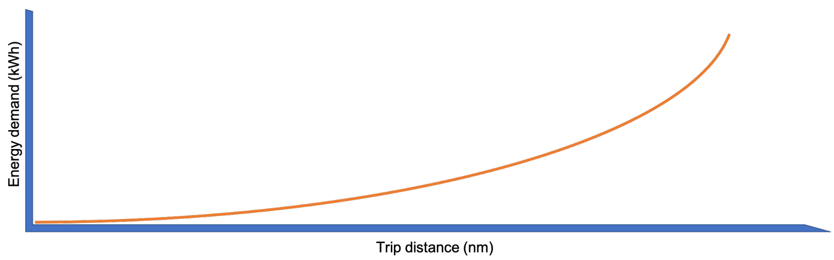


Figure 3.4: An example of the energy demand over the trip distance.

Energy storage Design parameters regarding the battery systems of the concept are required, before being able to create a design. These are obtained by performing a market analysis of the currently available batteries. From this, the battery best suited for the intended application is selected. Such battery systems require auxiliary systems, and are therefore are also considered. These topics are addressed in Appendix C.

[1] This is decided after consulting Bram Jongepier, Senior Specialist at DVNA, for an expert opinion

Energy supply Chapter 2 states that the power grid, and therefore shore power, will be increasingly powered by more renewable energy sources in the coming years. This will make the use of shore power to power a yacht an increasingly more sustainable source of energy. However, the extent to which this characteristic can flourish within the concept will be determined by the shore power supply available at marinas. This performance determines the time required to fully recharge the batteries. However, there is simply no general information available. It is therefore studied in Chapter 6.

Since the information is sector specific, a questionnaire is conducted among marinas worldwide to estimate this value. The questionnaire is conducted in collaboration with Water Revolution Foundation (WRF), as DVNA has a good relationship with them and WRF has valuable connections in the global marina industry. The questionnaire focuses on the following three topics:

1. Locate the marina within the geographical usage of a superyacht.
2. Determine the performance of the available shore power.
3. Identify their point of view on making the marina sector more sustainable.

Chapter 2 also notes that the geographical usage of superyachts is not fixed to a single location. While Type A is mainly found in the Mediterranean, Type B is also found in the Caribbean and along the US East Coast, and Type C is found worldwide. As mentioned earlier, this study focuses on Type B, therefore this questionnaire is also aimed at marinas in these areas. For comparison purposes, the available shore power from marinas in the other areas is also studied.

Benchmark yachts Benchmark yachts are selected for two reasons: to have a benchmark and to obtain design parameters. This will ultimately make it possible to check whether a version of the concept has the desired effect compared to the benchmark, and also to determine the amount of compensation weight that results from reducing the size of the generators. The selected yachts are presented in Chapter 4, together with their design characteristics and the rationale for the selection.

A division in yacht sizes must be made based on the linear relationship between waterline length and dimensionless cruising speed established in Chapter 2. It is concluded that as the size of a yacht increases, there is an increase in cruising speeds among the yachts in the fleet. This increase in cruising speeds leads to a higher required generator power, hence size. Added to this is the suggestion that the percentage of weight absorbed by the propulsion system relative to displacement is not linearly related to the size of the yacht. This so-called weight-share is expected to be higher for smaller yachts than for larger yachts, see Figure 3.5. Therefore, the potential reduction in generator size has a greater effect on smaller yachts than on larger yachts. This is taken into account by considering the following three length categories:

- **Small sized yacht**
- **Medium sized yacht**
- **Large sized yacht**

In line with these relations, it is expected that this decrease in generator size may outweigh the effects of the added weight of the batteries. This results in the hypothesis that the concept can best be applied in smaller sized vessels. This is therefore taken into consideration by implementing the defined three AER-versions (Section 3.2) into the three different sizes of yachts. This results in nine designs in total, summarised in Table 3.1. The general yacht size of these categories is determined by counselling experts at DVNA. They concluded that nowadays their small sized yachts have a length smaller than $50m$, medium sized yachts are between $50m$ and $80m$, and large sized yachts are longer than $80m$. A reference yacht that is suitable for this study is a Feadship with a length that fits the length of the category and deemed to be representative by an expert.

Table 3.1: All concept versions of which the effects are to be studied.

		AER version		
		Short	Mid	Long
Yacht size	Small	v1-S	v2-S	v3-S
	Medium	v4-M	v5-M	v6-M
	Large	v7-L	v8-L	v9-L

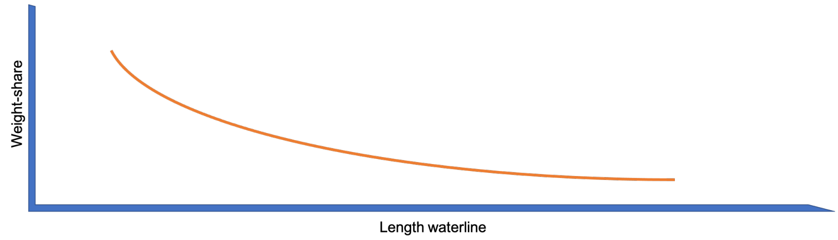


Figure 3.5: Expected correlation between yacht size and weight-share

3.3.2. Create designs

In the next phase, the obtained design parameters of the equipment and the insights in yacht usage are used to scale and create a parametric design of the concept versions of Table 3.1. The design method used is discussed in Chapter 7, then the actual parametric designs are created in Chapter 8. These are created in accordance with the design philosophy of Section 3.1 and are additionally bound by the following criteria:

- The yacht must be able to sail her transit speed using solely the generators. This sets a lower boundary condition (BC) for the generator size.
- The yacht must be able to sail at her top speed for a significant period of time. Exactly how long that is is to be determined from the operational profile. This results in a threshold value for the size of the battery and generator combined, as shown in Figure 3.6.

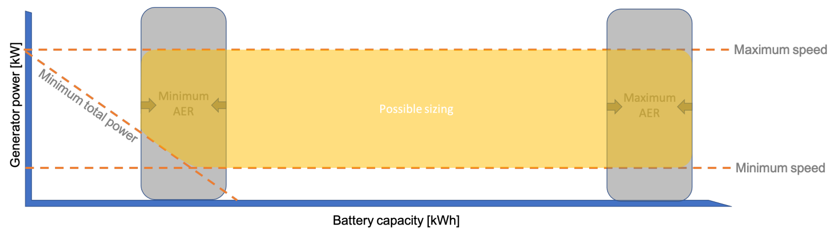


Figure 3.6: The sizing possibilities of the generator and battery module for the plug-in concept.

With these criteria set, the design is created in the following five steps:

1. The total available compensation weight is determined for each benchmark yacht. This consists of decreasing generator size, increasing displacement, and optimising tank usage.
2. The added power due to increasing draught is determined. This effect of the speed-power curve is determined with use of the admiralty coefficient method.
3. The total power demand is determined. Therefore, the hotel load and propulsive power demand are required. The hotel power is derived from the benchmark yachts. The propulsion power requirement is obtained from the operational data analysis, where a design speed is determined.
4. The generators are scaled to the required powers. This scaling results in a partition of the total available compensation weight being used.
5. The remaining available compensation weight is filled with batteries and accompanying auxiliary equipment. The total installed battery capacity results in a specific all-electric autonomy per concept version and corresponding impact. The AER is sailed at a speed determined in the operational analysis.

3.3.3. Check impacts

The impact of the different designs conclude on the main research question of this study, and are discussed in Chapter 9. This is accomplished by determining four different impacts, discussed separately below:

1. **Impact on design**
   First, the impact on design is determined by calculating the relative weight and volume share of the concept with respect to respectively displacement and gross tonnage.
2. **Impact on sustainability**
   The impact on sustainability is determined via a life cycle assessment (LCA). In this model, the life-cycle CO_2-eq emissions of an energy source are divided into two main phases: well-to-tank (WTT) and

tank-to-wake (TTW). The two phases combined evaluate the total well-to-wake (WTW) emissions. A LCA is performed for both energy sources - shore power stored in batteries and MGO. The ratio between both emissions is defined by the UF, as it describes the ratio between the distance sailed fully electric and the total sailed distance. The considered aspects are the production of MGO, electricity, and also that of batteries, plus the combustion of MGO.

3. **Impact on comfort**
   It is difficult to quantify the exact impact on comfort characteristics such as smell, noise, and vibrations. These are therefore evaluated in a qualitative manner, accompanied with an expert opinion of a design employee within Feadship.
4. **Impact on operation**
   At last, the impact on the operation of the vessel is determined. It shows what the new concept is capable of in operational terms by indicating in the trip-scatter which trips can be sailed fully electrically, which on the generators and which on the combined hybrid mode. This automatically indicates the trips that the concept is not able to make.

3.3.4. Test itinerary

To determine the extent to which the different versions use their installed batteries and the extent to which they are affected by available shore power, a test cruise is sailed in Chapter 10. During this cruise, the power and energy demand in different operating modes will be determined. It is expected that these requirements will differ significantly depending on the size of the yacht. The resulting energy demands are subsequently powered by different shore power performances throughout different shore power scenarios. The effect of this on the utilisation of the different versions of the batteries is monitored. From this, conclusions can be drawn about the feasibility of the different versions.

II

Technical Analysis

4

Design Benchmark

A benchmark yacht is needed in this study for several reasons: to have design parameters available; to determine the available compensating weight; and to determine the impact on design and operation. Information on these yachts, their characteristics, and the rationale for selection is provided in Sections 4.1 and 4.3. The diesel-electric benchmark configuration is discussed in Section 4.2.

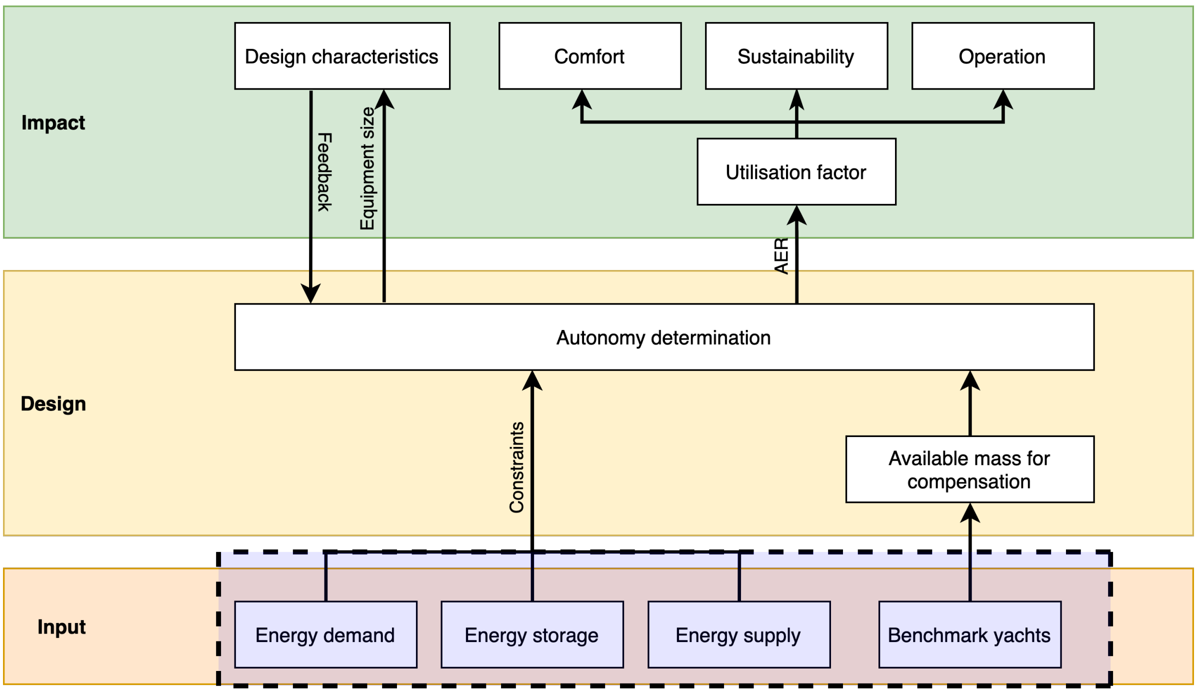


Figure 4.1: The design process flowchart, with the input part highlighted.

4.1. Yachts

A benchmark yacht sets the standard situation in which the concept is applied and from which the resulting effects are determined. In this study, three different yachts are considered - one for each of the three length categories. Which yachts these are and the rationale on which the choice is based is as follows:

- **Yacht-S** - $\leq 50m\ L_{wl}$
  This yacht is considered because it is a current design number at DVNA with a waterline length of $45m$, thus fitting into the small length category. No specific propulsion system has yet been designed for this design number. Several options are being considered for this, of which the plug-in hybrid electric concept is one option being considered.

- **Yacht-M** - $50-80m\ L_{wl}$
  This yacht is considered because it is regarded as an average Feadship in terms of size and design. Therefore, she is more often considered in studies of DVNA. In addition, she falls into the category of medium sized yachts with a waterline length of about $75m$. She is a relatively new yacht equipped with a diesel-direct configuration.
- **Yacht-L** - $\geq 80m\ L_{wl}$
  This yacht is being considered because she is often used as a benchmark yacht in studies of DVNA. She has a waterline length of approximately $100m$ and thus fits into the large length category. This yacht is also a relatively new Feadship equipped with a large diesel-electric configuration.

4.2. Diesel-electric Configuration

The benchmark configuration is a diesel-electric configuration with generators in line with associated auxiliary equipment and electric motors. The auxiliary equipment considered is a switchboard and a frequency converter. A configuration with a reduction gearbox in front of the propeller exists but is not common and is therefore not considered. Figure 4.2 shows the defined benchmark propulsion system with the corresponding individual efficiencies of the components. The installed converter behind the generator is a full-wave rectifier. For simplicity, a constant efficiency over the entire operating envelope of the generator set and the electric motor is assumed, as well as for the remainder of the equipment. The number of components installed is also neglected as the efficiency remains the same - e.g. two generators of $1000ekW$ each or a single generator of $2000ekW$ produce the same electrical brake power. The configuration is powered by Marine Gas Oil (MGO), also known as Distillate Marine grade A (DMA) - a marine distillate that contains no trace of residual fuel and is therefore low in sulphur.

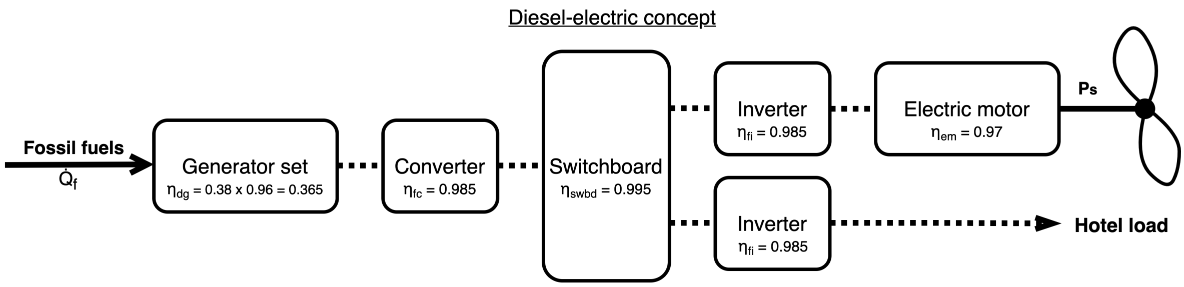


Figure 4.2: A one-line diagram of the considered benchmark diesel-electric configuration with corresponding efficiencies.

4.3. Design characteristics

The design benchmark is set by the design characteristics of these considered yachts. The design characteristics considered are waterline length ($L_w l$), gross tonnage (GT), displacement (Δ), cruising speed (V_{cruise}), maximum speed (V_{max}), associated speed-power curves ($v_s - P_s$) and hotel power (P_{hotel}). These design characteristics of the benchmark yachts are shown in Table 4.1. The speed-power curve of Yacht-S shown in Figure 4.3 is an estimate calculated by naval architect experts from DVNA. The speed-power curves of Yacht-M and Yacht-L shown in Figure 4.4 and 4.5 consist of actual measured shaft powers during sea-trials. The hotel power is the rated constant required hotel load in the Mediterranean. This area was chosen because previous studies concluded that it is home to most of the Feadship fleet at least ones a year.

Table 4.1: The considered design characteristics of the benchmark yachts.

Name	Length	Volume	Displacement	Speeds		Hotel power
	L_{wl}	V	Δ	v_{cruise}	v_{max}	P_{hotel}
	[m]	[GT]	[t]	[kts]	[kts]	[kW]
Yacht-S	45.0	500	361.8	10.0	17.0	65.0
Yacht-M	75.0	1600	1318	12.0	18.5	180
Yacht-L	100	4800	3390	14.0	18.5	400

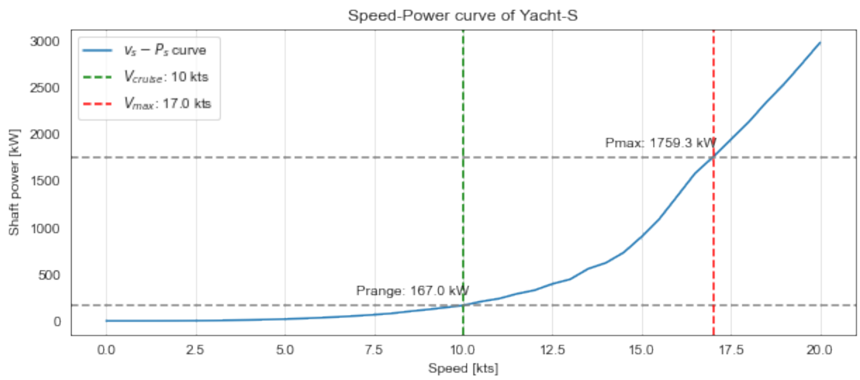


Figure 4.3: The estimated speed-power curve of Yacht-S.

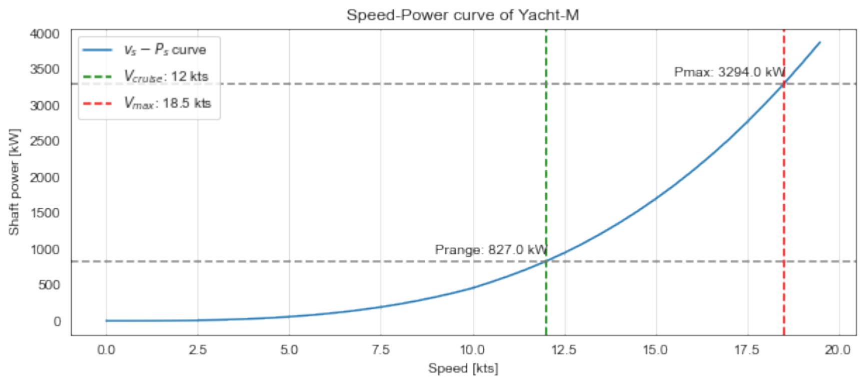


Figure 4.4: The measured speed-power curve of Yacht-M during sea-trails.

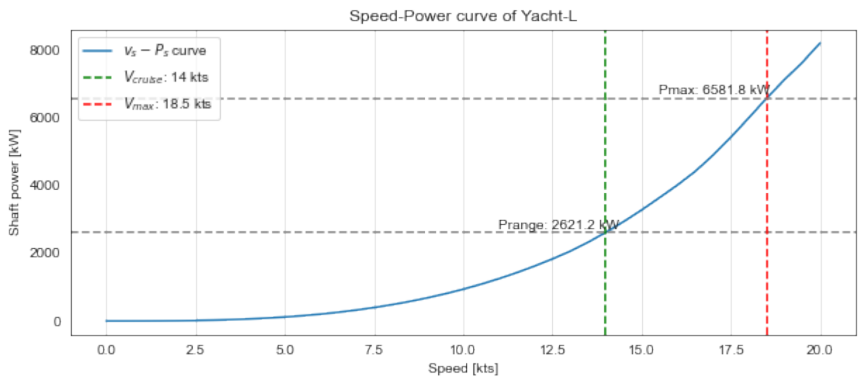


Figure 4.5: The measured speed-power curve of Yacht-L during sea-trails.

5

Operational Voyage Data Analysis

The currently available operational analyses lack information about short trip behaviour, and the AIS data is linearised between timestamps, as described in Chapter 3. This chapter proposes a solution to these challenges. Feadship has generic AIS -data at its disposal. Since the proposed new concept does not depend on operational type (A/B/C), the generic AIS data is sufficient. The operational analysis is performed with the aim of obtaining statistical insights on the required endurance and performance of the new concept.

5.1. Improve AIS analysis

In order to provide a solution to the problem uncovered in the AIS data, the root cause must first be determined. The available AIS dataset of Feadship is shown in the scatter plot of Figure 5.1. After careful review of the AIS data in collaboration with Feadship staff, the root cause of the linear behaviour was found. It shows this linear behaviour due to the sampling frequency of the data.

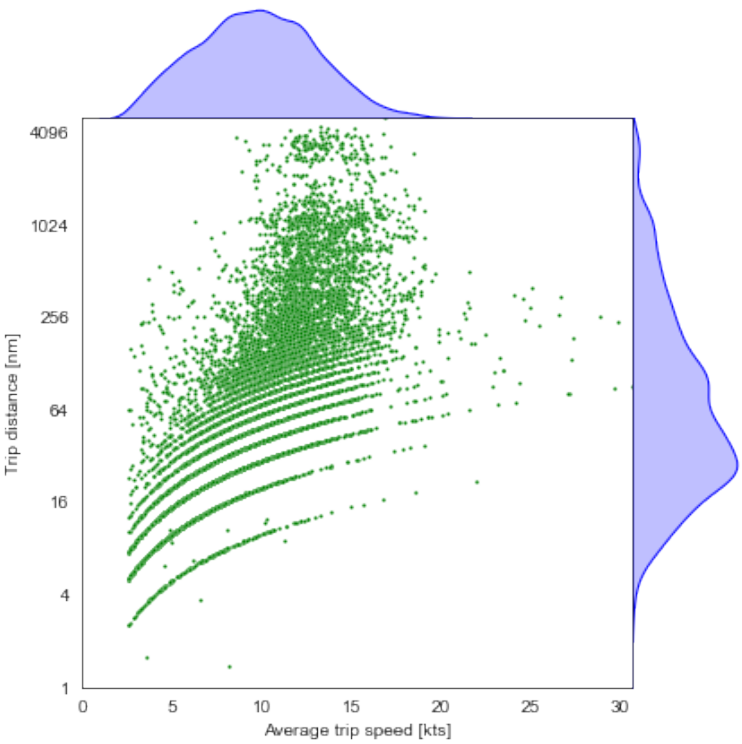


Figure 5.1: The trip scatter of the AIS-data with an hourly sample-period.

Feadship has developed a AIS data analysis algorithm to determine the trips sailed from an AIS dataset. This algorithm uses the timestamp in combination with the associated speed to determine if the trip has ended. If the speed at a given timestamp is less than $2.5kts$, the algorithm defines the trip as completed. Since the timestamp only occurs with a certain sampling period in between due to the sampling frequency, the trip only ends at a timestamp with n- times the sampling period in between.

In the original case, this algorithm is applied to a large AIS dataset with a low sampling frequency. In this case, the sample period between timestamps is a single hour, so a trip can only have a duration of $n \cdot 1$ hours. The characteristics of this dataset are shown in Table 5.1. These trips are plotted in the trip scatter shown in Figure 5.1. In this figure, the trip distance is plotted versus the average trip speed of a single completed trip. Note the logarithmic scale on the y-axis. Additional information is plotted on both axes in the form of a histogram trend line of the data plotted on each axis.

The data points in the trip scatter plot have a relation to the duration of a single trip, as shown in Equation (5.1). The parallel lines shown in Figure 5.1 resemble this relation with the sampling period.

$$\text{Trip duration} = \frac{x}{v} = \frac{\text{Sailed distance}}{\text{Average trip speed}} \tag{5.1}$$

The proposed solution is to use a dataset with a high sampling frequency. The obtained dataset is a two-week recording of the Feadship fleet with a sampling period of 3 minutes. After processing this dataset using the processing algorithm, this resulted in the characteristics as shown in Table 5.1 and the trip scatter shown in Figure 5.2. The general behaviour is quite similar to that of the scatter plotted earlier. However, the lower part of the figure shows that yachts also sail short trips at varying speeds and not only at lower speeds. This shows that the higher frequency dataset resolves the linearisation of the results. This dataset is considered too small to lead to relevant conclusions, nevertheless it seems to validate the trends from the larger dataset. To enlarge the usability of this dataset for future research and be able to draw potentially relevant conclusions, Feadship is expanding its fleet with yachts that have high frequency AIS sampling equipment installed on board.

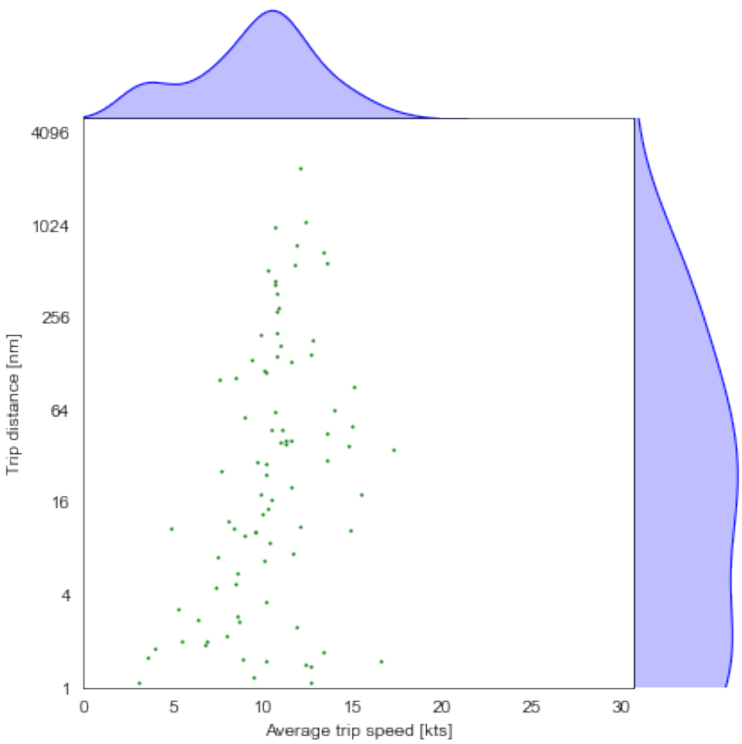


Figure 5.2: The trip scatter of the AIS-data with a three minute sample-period.

For this study, it was decided to merge both the low sample frequency data and the high sample frequency data. This would reflect the usage of a yacht as best as possible with the available data at hand. The resulting data characteristics are shown in Table 5.1, and are equal to almost 22 years of recorded data. In which 50 unique yachts sail a distance of slightly more than 105 times around the globe. The resulting trip scatter is shown in Figure 5.3. When in the remainder of this study is referred to AIS-data or dataset, this combined dataset is meant.

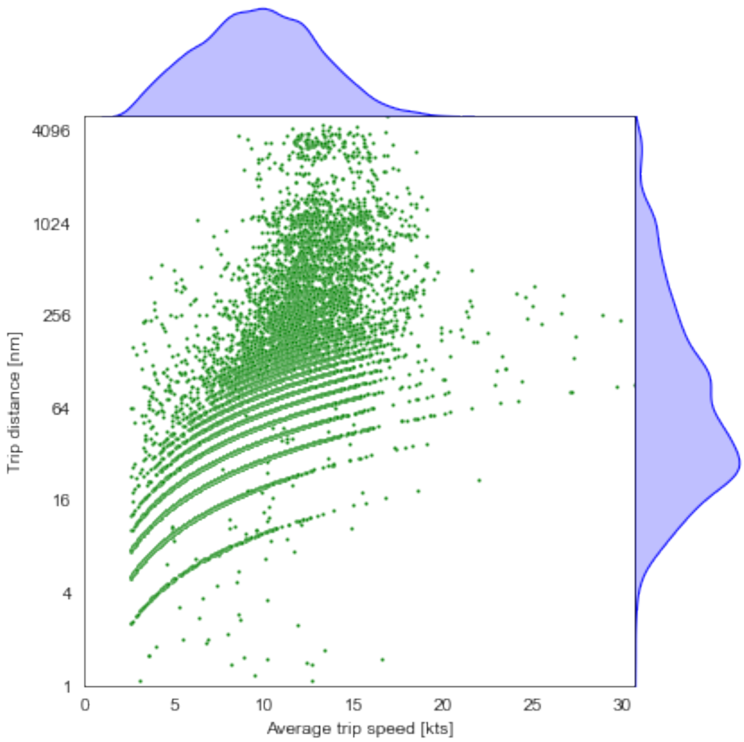


Figure 5.3: The trip scatter o both AIS-datasets combined.

Table 5.1: Characteristics of the different AIS-datasets.

Characteristic	Low frequency	High frequency	Combined
Number of uniquely observed yacht	50	17	50
Number of recorded trips	10990	102	11092
Total uptime [hours]	190308	1085	191393
Total sailed distance [nm]	2267732	12349	2280081

5.2. Improve operational analysis

To improve the AIS analysis, additional statistics are generated. Therefore, the histograms plotted on each axis of Figure 5.3 are first reviewed separately, after which conclusions regarding the trip scatter are drawn. On the x-axis of the trip scatter, a histogram of average trip speed is plotted, and on the y-axis of the trip scatter, a histogram of the trip distance is plotted on a logarithmic scale.

5.2.1. Design speed

The speed histogram isolated from the top of Figure 5.3 is shown in Figure 5.4. This figure provides information about what average speeds are most often sailed, and thus what average trip speeds the new concept will most likely sail. This provides information on whether the operational profile of a yacht matches the operational capabilities of the concept, or whether the concept needs to be designed to sail in such a way that it is capable of sailing at these speeds. The influenced design parameter of the yacht is the required installed power, due to the relation between the speeds sailed and the required installed power of the concept. Since lower speed cruises have lower power requirements than higher speed cruises, this factor is the main design driver for the concept's power requirements. In addition, the design speed concluded on is used as the constant speed in the determination of the AER per concept version.

The figure shows that the most often sailed average trip speed is almost equal to the mean average trip speed. The mode (or modal value) is 10.5kts, while the mean is 9.7kts. This indicates that it is sufficient to design for a single operating speed. This is lower than the mean design cruise speed of the fleet, which is 12.0kts. This discrepancy is caused by the fact that it is not a measurement of the most frequently sailed speed during a trip, but only an average speed during the trip. The lower speeds sailed when entering or leaving a marina cause a reduction in that figure, and since the more frequently sailed trips have a shorter distance, this has a significant impact. Looking at the most frequently sailed speeds during a trip, taken from an internal study by DVNA (see Figure 5.5), a peak is seen at an average cruising speed of 12.0kts. This is the actual speed at which will be operated on most frequently. Therefore, the design speed of the concept is focused to be the design cruising speed of the yacht.

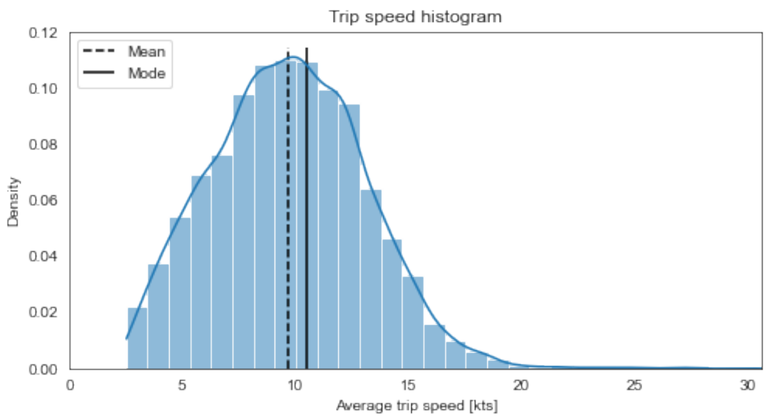


Figure 5.4: The histogram of the average trip speeds.

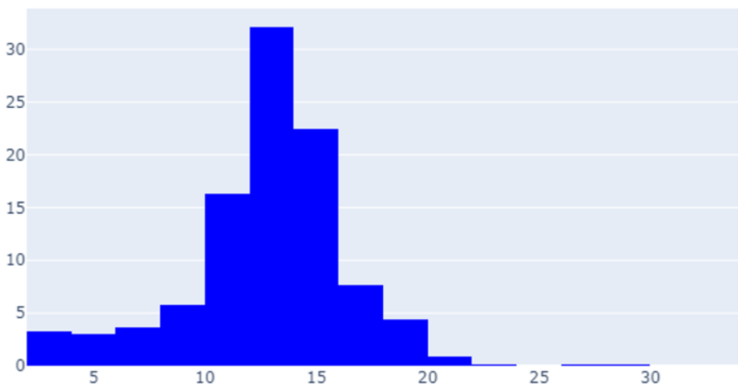


Figure 5.5: The histogram of the most frequently sailed speeds.

In Section 2.4, the Water Revolution Foundation showed that the speed profile of a yacht depends on the length of the waterline. They showed a negative correlation between waterline length and Froude number, implying that longer yachts generally sail at higher cruising speeds than shorter yachts. This correlation is verified by dividing the dataset into the three defined length categories. Table 5.2 shows the number of yachts present in a specific length category.

Using the waterline lengths of the benchmark yachts in the categories, the length-specific Froude number is determined. The speed profiles of the length categories are visualised in Figure 5.6. The length categories clearly show the shift towards higher average trip speeds as the waterline length increases, confirming the findings of the Water Revolution Foundation. This is accounted for by using the waterline length-dependent cruising speed to determine the design speed of a concept version, as this represents the actual cruising speed sailed by that yacht. These speeds are given in the last column of Table 5.2.

Table 5.2: The number of yacht present in a specific length category and waterline length-dependent cruising speed.

Length category	Number of yachts	Length dependent cruising speed
Up to 50m	16	13.9
50m to 80m	25	13.5
80m and up	9	11.8

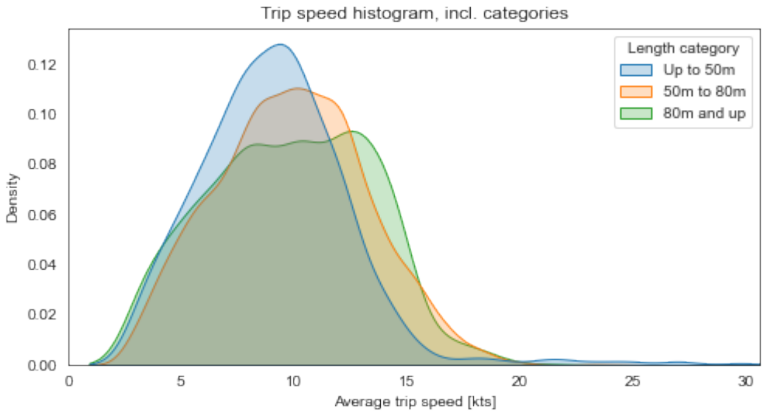


Figure 5.6: The histogram of the average trip speed, including categories.

5.2.2. Design range

The trip distance histogram isolated from the right-hand side of Figure 5.3 is shown in Figure 5.7. This provides information on what distances are sailed most often, and thus about which distances the new concept will most likely sail. This information affects the all-electric endurance required, and thus the total electrical energy demand, of the new concept. It must be noted that the data is plotted on a logarithmic base 2 scale.

Within the AIS data used, no distinction is made as to whether the trips are port to port, anchorage to anchorage, port to anchorage, or vice versa. These are all defined as trips within this study as it was out of scope to improve Feadship's AIS-data analysis algorithm.

The data shows that the most frequently sailed trip distance is 23.8nm, but since the figure is right skewed on a logarithmic basis, the mean is 205.6nm. This is a large discrepancy between the two values, suggesting that there is no single specific electrical design distance for the concept. As a result, the AER is variable in the design phase. The majority of the trips range between approximately 25nm to 200nm, so it is expected that the AER should fit within that range to have a significant impact.

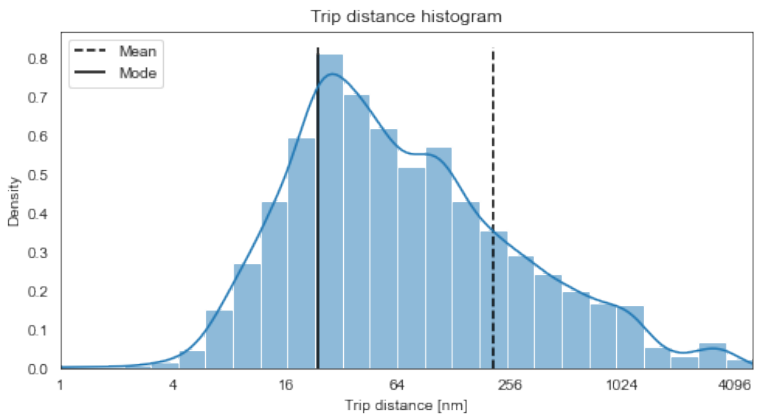


Figure 5.7: The histogram of the sailed trip distance.

To what extent a specific AER can have a theoretical maximum impact on the full range capabilities and to what extent this increases over the course of the total sailed distance is determined with use of a cumulative density function (CDF) of the data. Since the principle of the concept is to sail part of the total distance on shore power, a possible theoretical maximum effect can be indicated on part of the full range. This CDF of the obtained dataset is shown in Figure 5.8.

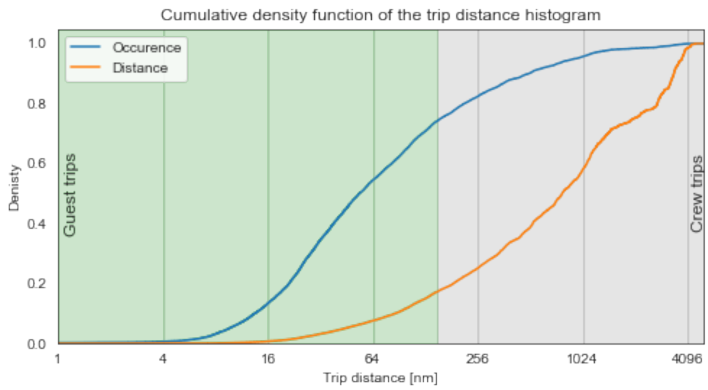


Figure 5.8: The cumulative density function of the sailed trip distance.

The two lines in the CDF, a blue line and an orange line, represent the data. These lines represent the share of the total number of trips and the share of the total distance sailed, respectively. This gives an indication of the impact of a particular AER. Since the mode of the trip distance is $23.8nm$, a steep incline in occurrence is observed for shorter distances. However, the sum of these many short-distance trips represents only a small fraction of the total distance travelled, so that the distance curve has a rather low slope. On the contrary, only a small number of long-distance trips have a large contribution to the distance share. A slight increase in the occurrence share at longer distances therefore leads to a steep incline of the distance curve.

In the figure, two areas are coloured, a green area and a grey area. These areas represent which part of the trips is sailed with guests on board, and which part is sailed with only crew on board. Using an expert opinion[1], it is estimated that the maximum distance sailed with guests on board is approximately $150nm$. It must be noted that in the available dataset, no info on guest or crew-only is available. The value used here is therefore a rough estimate, but based on a maximum guest trip duration of approximately 8 hours at high speeds ($\geq 18kts$). This duration is based on the trip duration histogram shown in Figure 5.9. Again, this is a right-skewed figure with a mean of 17.3 hours and a mode of 3.0 hours. A middle value is arbitrarily chosen that corresponds to a sailing time between breakfast and dinner.

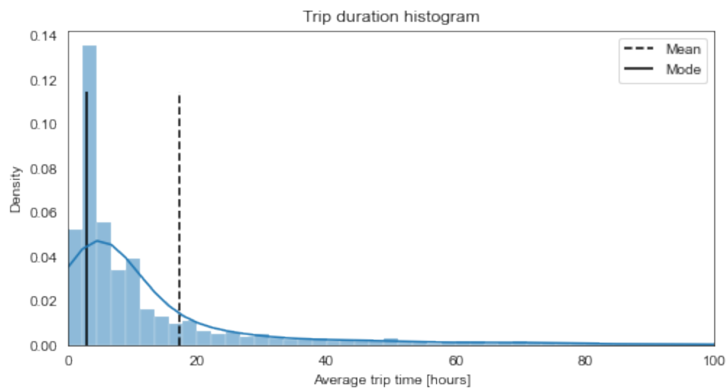


Figure 5.9: The histogram of the trip duration.

[1]This is decided after consultation with Bram Jongepier, Senior Specialist at DVNA, for an expert opinion

5.2.3. Trip scatter

The trip scatter shows that the majority of the shorter trips are sailed at lower speeds than the mode of $10.5kts$. When the trip distance increases, the average trip speed increases to a value closer to that mode. The long distance trips without guests on board ($\geq 150nm$) have their speeds focused around the average design cruising speed of $12.0kts$. This would indicate that the trips with guests on board are most often sailed at lower speeds than cruising speeds.

A correlation between trip distance and trip speed would confirm this suggestion, and indicate the feasibility of the concept, or to what extent the concept should be able to operate. An exponential regression analysis of the data is performed with Equation 5.2 to prove a possible correlation. The trip scatter with a suggested correlation is shown in Figure 5.10.

$$d = exp(a \cdot v_s + b) \tag{5.2}$$

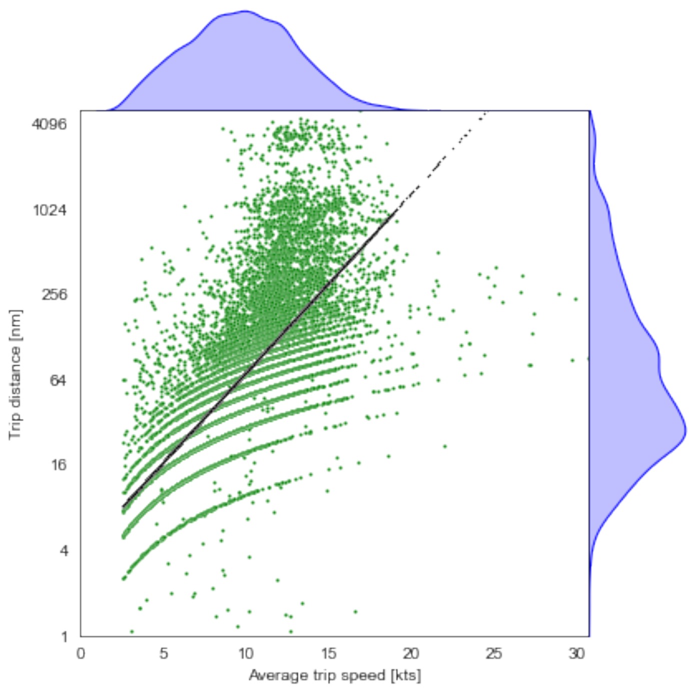


Figure 5.10: The trip scatter with a exponential regression analysis.

The characteristic behaviour of yachts has a mild correlation between both trip distance and speed, yet deemed too mild. This is because different operational aspects present in different zones of the trip scatter are not taken into account within this regression.

- A suggested maximum cruise duration in the top left zone.
- An suggested influence of guest presence in the middle trip distance zone.
- A fuel capacity limit in the top right zone.

It makes no sense to sail such great distances as a Mediterranean crossing at the average speed at which one normally has dinner cruises along the coast. This would take up an unnecessary amount of time, so there are no trips in that zone. The dispersion of trip speeds in the middle trip distance zone can possibly be attributed to the presence of guests on board. These could require fast transit between destinations, or rather a moderate trip along the coastline. The combination of both would explain the dispersion. The focus of long-distance trips ($\geq 1000nm$) at about 12 to 15 knots is due to limited fuel capacity on board, resulting in a maximum stored energy. Due to the third power relationship between power and speed (see equation (3.2)), the energy requirement is much higher at higher speeds. As a consequence, sailing over longer distances at these higher speeds is not possible because too little energy is stored on board.

6
Shore Power Availability

Part of the design philosophy of the concept under study is to sail part of the distance on shore power stored on board. Therefore, insight into the shore power connections available worldwide is needed. To gain this insight, a survey among marinas located around the world is conducted. The questionnaire itself and the results are attached in AppendixD. The resulting average shore powers are analysed in this chapter to determine an average charge power per residing yacht area and per yacht size category. In addition, the difference between shore power and charging power is addressed. The required charging time is then used to evaluate the feasible battery capacities under three different charging infrastructure scenarios.

6.1. Charge power

The determined shore power averages (P_{shore}) indicate the current average power of the connection in their specific area. These are summarised in Table 6.1. These are used to determine the average maximum amount of energy that a shore connection can deliver to a yacht (E_{shore}) in a given period of time - this is called the shore power capacity. Equation (6.1) shows that this capacity is entirely dependent on the total time a yacht is berthed in a marina (t_b).

$$E_{shore} = P_{shore} \cdot t_b \tag{6.1}$$

The amount of available shore power capacity over time spent in a marina is shown in Figure 6.1. The survey found that yachts spend on average between twelve hours and two days in a marina. Therefore, these two time periods are used as benchmark parameters and shown in the figure. This figure shows a variation in shore power capacity across all areas, but particularly an unsatisfactory shore power supply in the Caribbean.

Table 6.1: The current average available shore powers in different regions.

Area	**Adriatic Sea**	**Caribbean Sea**	**Mediterranean Sea**	**Other areas**
	[kW]	[kW]	[kW]	[kW]
Shore power	494	109	594	541

This shore power capacity does not directly indicate the amount of energy available to charge the battery. In fact, part of the available shore power is used for the hotel operation of the yacht (P_{hotel}). The hotel power values of the benchmark yachts in Chapter 4 are used. The hotel power is subtracted from the available shore power to obtain the available charging power (P_{charge}), see Equation 6.3.

$$P_{charge} = P_{shore} - P_{hotel} \tag{6.2}$$

$$E_{charge} = P_{charge} \cdot t_b \tag{6.3}$$

The hotel power demand varies for different yachts, but in general it can be stated that a larger yacht with more GT has a larger hotel power requirement than a smaller yacht. More specifically, this leads to small yachts having a larger charging capacity available than larger yachts. The result is that, in addition to regional differences, the available charging capacity also varies within the specified length categories. The resulting average available charging power for the benchmark yachts across regions is shown in Table 6.2.

Table 6.2: The average available charge powers across the different regions and yacht sizes.

Yacht	Adriatic Sea [kW]	Caribbean Sea [kW]	Mediterranean Sea [kW]	Other areas [kW]
Yacht-S	429	44	529	476
Yacht-M	314	-71	414	361
Yacht-L	94	-291	194	141

These charging powers clearly indicate that a smaller yacht can charge significantly more than a larger yacht, resulting in shorter charging times. A negative charge power indicates that, on average, a yacht will not be able to make a connection that meets its power requirements, and thus will never be able to charge its battery.

As mentioned earlier, the power supply in the Caribbean is very poor, so none of the vessels are able to make a connection or charge their batteries sufficiently. In addition, Yacht-L has limited charging power available in all regions due to its high hotel power requirement. Yacht-M is able to charge in the remaining three regions, albeit at a slightly lower power than Yacht-S. This yacht has the highest available charging power in the three remaining regions, as predicted.

It is possible to draw conclusions from these trends, but the absolute numbers should be treated with caution. In Appendix D, it is shown that the deviation per region of available shore power is very large. The Mediterranean Area has a standard deviation of up to 91%! This must be taken into account when considering the presented figures.

6.2. Shore power scenarios

The low average available charging power might indicate that the plug-in hybrid concept is not feasible for some yachts in some regions. However, the large variations across all regions suggest that these numbers should not be relied upon completely. In addition, the available charging power is also highly dependent on the marinas visited. Therefore, three shore power infrastructure scenarios that a yacht might encounter during a cruise are considered. These scenarios consider a current, future and desired infrastructure.

1. In the first scenario, the current average shore power availability is considered as the available power.
2. In the second scenario, the expectation that the infrastructure will improve in the future is considered. According to the results of the questionnaire, the expectation is that the available shore power will increase with half of the current available power.
3. In the third scenario, a desired situation is considered where the infrastructure improves in the future and the yacht visits marinas with a more efficient shore power connection more frequently. This results in an available shore power supply that is approximately twice that of the current infrastructure. Other areas are slightly lower due to the uncertainty of globally spread marinas.

The resulting available shore powers among the yachts for the different scenarios are shown in Table 6.3. These arbitrarily chosen values per scenario are based on the expectations resulting from the survey results. Table 6.4 shows the resulting charging powers of the different yachts.

These scenarios show that the feasibility of the envisioned concept increases significantly with the increase of available shore power. This effect is present for all yacht sizes and in all areas except the Caribbean. In addition, Yacht-L is expected to require significantly larger batteries. Therefore, even the charging capacity in the Mediterranean is expected to be insufficient. A market movement towards building many plug-in concepts will improve the supply of shore power and further increase the feasibility of the concept.

Table 6.3: The available shore powers across the different regions for the different scenarios.

Scenario	Adriatic Sea [kW]	Caribbean Sea [kW]	Mediterranean Sea [kW]	Other areas [kW]
Current	494	109	594	541
Future	750	150	850	625
Desired	950	225	1250	750

Table 6.4: The available charge powers of the different scenarios in the different regions and yacht sizes.

Yacht	Scenario	Adriatic Sea [kW]	Caribbean Sea [kW]	Mediterranean Sea [kW]	Other areas [kW]
Yacht-S	Current	163	-15	255	169
	Future	429	44	529	476
	Desired	885	160	1185	685
Yacht-M	Current	314	-71	414	361
	Future	570	-30	670	445
	Desired	770	45	1070	570
Yacht-L	Current	94	-291	194	141
	Future	350	-250	450	225
	Desired	550	-175	850	350

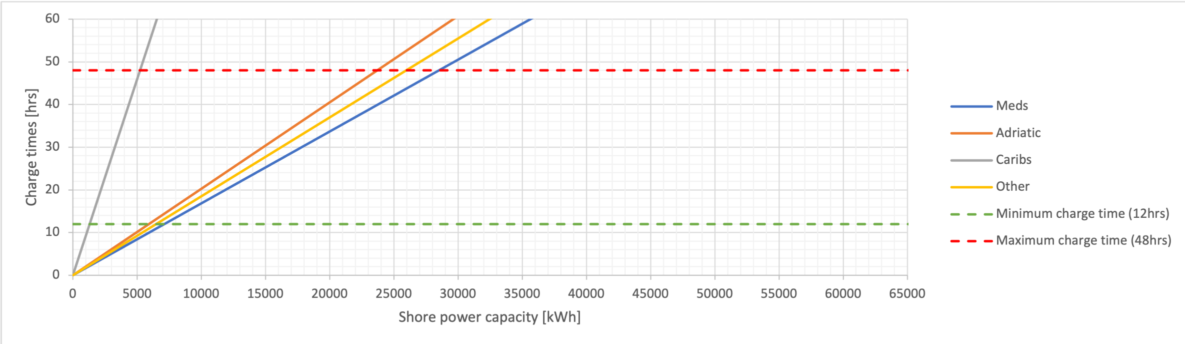


Figure 6.1: The averaged current available shore power capacity.

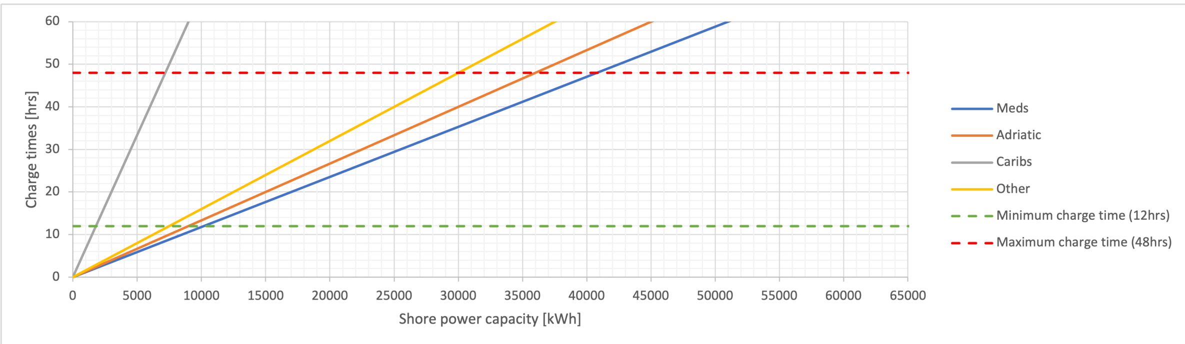


Figure 6.2: The expected future available shore power capacity.

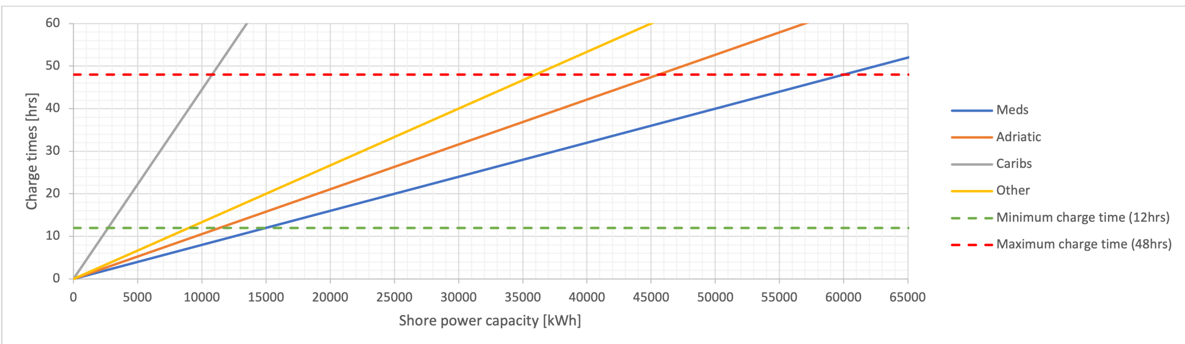


Figure 6.3: The desired available shore power capacity.

III

Concept Design

7 Data Driven Design

This chapter explains the steps that are applied to design the different concept versions. The design decisions made are based on the results of the operational data analysis. The design philosophy is to minimise the impact on the current design. Therefore, three methods to compensate for the added weight are explained in Section 7.3. The impact of the additional displacement weight on the design characteristics and the corresponding required adjustment of the speed-power curves is explained in Section 7.4. The scaling of the required equipment of the configuration is explained in Section 7.5. This includes how the auxiliary equipment is scaled to achieve the required powers. Section 7.6 explains how this available compensation weight is used to determine the all-electric range (AER), but first the design scope is defined in Section 7.1 and the design process is explained in Section 7.2. The actual parametric concept designs are created in Chapter 8.

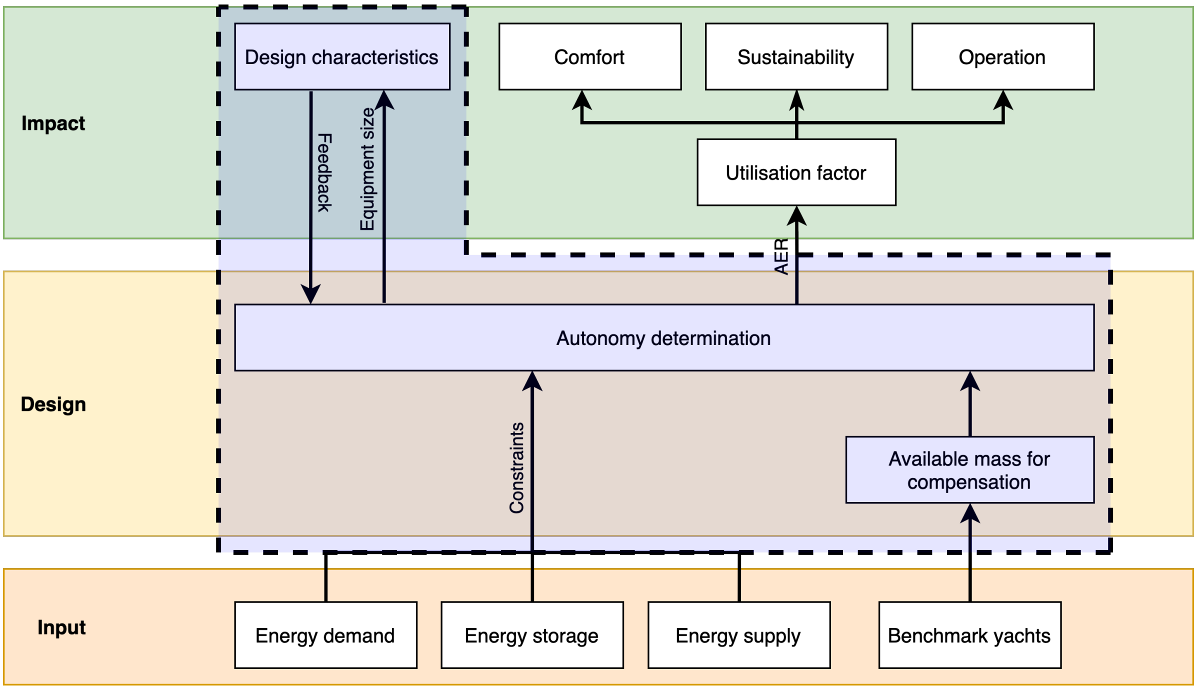


Figure 7.1: The design process flowchart, with the design part highlighted.

7.1. Design scope

Defining the scope of design is essential. This focuses the design of the envisaged concept on a workable number of options, rather than an infinite number of options. This section looks at the results of the technical analysis to define the scope of the concept design.

- The concept design is limited to the configurations presented in the introduction. The configuration with corresponding efficiencies is shown in Figure 7.2. The design freedom is limited to altering the size of the required components. It is known that for certain components a different type can be chosen, which then influences the composition of the components, for example a permanent magnet electric motor eliminating the inverter. In this way, the concept could be optimised, but as mentioned in the introduction, this research is limited to explore different options, instead of optimising a single version. Furthermore, similar to the benchmark configuration of Section 4.2, the number of specific installed components is neglected. Only the design parameters of the specific machinery as a whole are taken into account.

  Compared to the presented benchmark in Figure 4.2, the machinery that is added are the battery and the accompanying converter (coloured green). The generator, accompanying converter and the switchboard (coloured yellow) are the components that are to be re-scaled. The proposed configuration is an intermediate version that is expected to score well on performance, controllability, and thus safety. The presented efficiencies are averaged constants and deemed market representative.
- The design speed is set to be the waterline length-dependent cruising speed defined in Chapter 2. This is in line with the conclusions of Section 5.2.1. As a result, the installed generators do not need to have more power than required at cruising speeds.
- The addition in displacement of the yacht is the design variable. This results in more weight being available for batteries, yielding a differing autonomy per concept version. This is in line with the conclusions of Section 5.2.2.

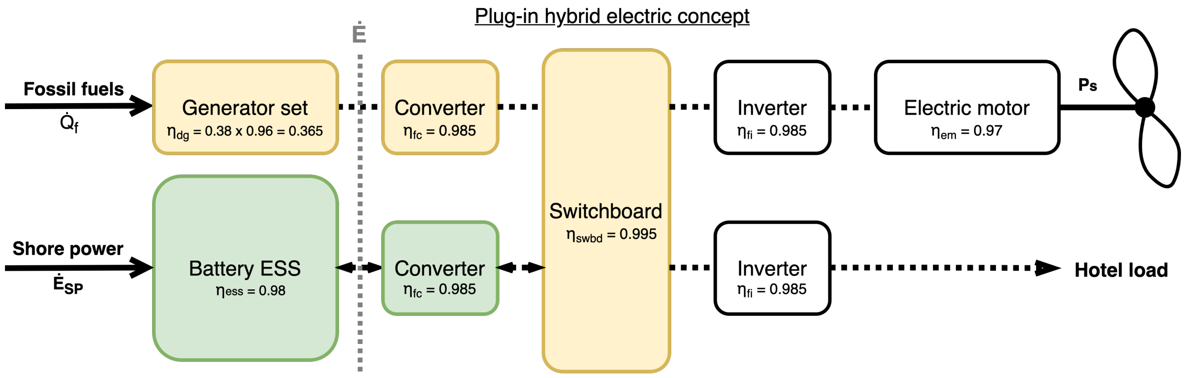


Figure 7.2: A one-line diagram of the considered concept configuration.

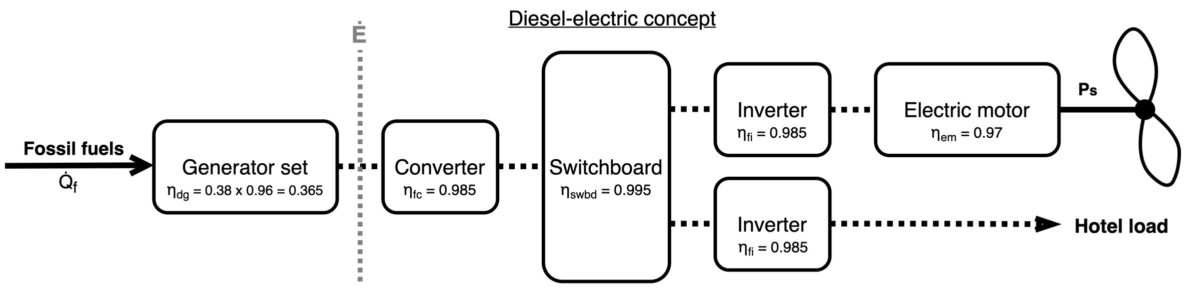


Figure 7.3: A one-line diagram of the benchmark configuration.

7.2. Design process

The autonomy is the crucial parameter in the design of the new concept. It is therefore of great importance to determine this in a systematic way. The process is shown in Figure 7.4. This full electrical range depends mainly on the amount of on-board stored energy, hence depends on the available weight, so first the maximum capacity that can possibly be placed on-board is determined. First, the total available compensation weight is determined. This results in an increased displacement for specific concept versions, therefore the speed-power curves have to be adjusted. With the total available weight and adjusted speed-power curves known, the equipment of the concept can be scaled and implemented into the vessel. This results in an available weight for the battery, from which the autonomy can be determined.

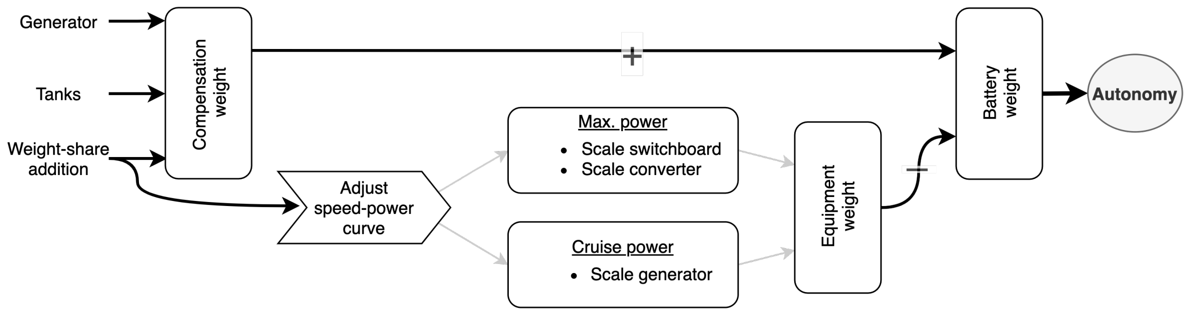


Figure 7.4: A process diagram of the required steps to determine the autonomy.

7.3. Available compensation weight

The weight available for compensation is an important feature that mostly determines the viability of the plug-in hybrid concept. The more weight available for compensation, the more batteries can be placed on board, thus more installed capacity resulting in an increased AER. This section describes the three methods that result in the total amount of available weight for compensation: decreasing the generators; optimising tank usage; increasing displacement.

1. The principle of the first method is to decrease the generators to the minimum power required. The DE-configuration presented in Figure 4.2 is used as a base case, in which the generators are scaled to the required power. This scaling is done later on in the design. This results in the configuration being completely removed in this step. It must be noted that only the components of the DE-configuration that are being re-scaled during the design of the new concept are removed. The resulting available weight is determined in the following steps:
   (a) Check if the original installed configuration is a DE or a DD-configuration.
      - If it is a DE-configuration, then proceed to the next step.
      - If it is a DD-configuration, then the configuration is converted to a DE-configuration. This is accomplished by deleting the installed steering equipment plus propeller, and replacing it with thruster propulsion modules of the required power plus the required electrical auxiliary equipment. This includes the frequency converters and the switchboards.

   (b) The installed engines, gearboxes, generators, auxiliary generators/ESS and enclosed mechanical fluids are removed out of the yacht. This results in a yacht with a DE-configuration, yet only with a generator set missing.
   (c) The generator sets are later scaled to the required powers, resulting in a new weight and volume of the generator set.
2. An additional way to save weight, specific to yachts, is to optimise tank usage according to the operational usage. Currently, yachts have their fuel tanks filled as much as possible, thereby having the full range at their disposal at all times. This range is often between 4000 to 5000 nautical miles. After reviewing the trip distance diagrams in Chapter 5, it is concluded that this is most often not necessary to meet the required range of the sailed trips. This is especially not necessary for trips with guests on board, as these have an estimated range of $\approx 150nm$. Therefore, it has been determined that during a guest stay a tank fill rate of 75% is sufficient to satisfy all trips except the Atlantic Ocean crossing. On the contrary, when yachts cross that Atlantic Ocean, the full range and thus a tank fill rate of 100% is required. However, during such crossing there are no guests and only a few crew members on board. The

crew present is only the crew required for that crossing. With less people on board, a smaller amount of fresh water is required on-board. The required quantity during a crossing is estimated at 30% of the total fresh water tank capacity. Additional tanks that are able to save weight during a crossing are the pool and the helicopter fuel tanks. During a crossing, these tanks are considered empty. An empty helicopter fuel tank can be an operational problem, as this cannot be discharged easily. Nevertheless, it will be considered, as it can be taken into account in operational planning.

It must be noted that this method of saving weight by optimising tank usage results in significantly stringent operating conditions, as the intact/damage stability is most likely to change significantly. The compensation weight available is the weight of the operating condition with the smallest difference between the original state and the two discussed states. The original state is the state with all discussed tanks 100% filled.

Table 7.1: The tank fill rate under different operating conditions.

Tank	**Installed capacity**	**Used capacity**	
		Guest stay	Crossing
Fuel oil	100%	70%	100%
Fresh water	100%	100%	30%
Pools	100%	100%	0%
Heli fuel	100%	100%	0%

3. The third method is to increase the displacement of the vessel, defined as weight-share addition ($WS_{addition}$). The designer is allowed to increase the draught of the yacht by adding a maximum of 5% on top of her displacement. This minimises the impact on the design. Furthermore, 5% is considered by DVNA as a standard marge during early stage design stages and therefore implemented with little effort. This is set as a maximum design condition. The minimum design condition used is the available compensation weight mentioned earlier. This is the amount of weight that can be freely added (0.0% weight-share addition). Both minimum and maximum design conditions define the short and long AER version of the concept, as more available weight for the batteries results in a greater autonomy. The middle version is defined as the average of both weight additions, i.e. 2.5%.

Table 7.2: The weight-share addition per AER version.

AER version	**Weight-share addition**
Short	0.0%
Mid	2.5%
Long	5.0%

The combined available weight of the tank fill rate (m_{tanks}), decrease generator size ($m_{generator}$), and weight-share increase of displacement (Δ), is the total weight available for compensation of the added weight of the battery and generators of the proposed new concept.

$$m_{avail} = WS_{addition} \cdot \Delta + m_{tanks} + m_{generator} \tag{7.1}$$

7.4. Adjustment speed-power curves

Figure 7.1 shows that feedback on design characteristics is provided and used in the design process. The design characteristic considered is the impact on the speed-power curve of the vessel when it is weighted with the battery. The admiralty coefficient method is used to determine the adjusted speed-power curve. One can also use a power and energy prediction method specifically for early stage design to predict the required power and energy demands. Such a method specific to energy prediction of yachts in early-stage design is presented in the study of Odendaal [44]. However, due to the large number of input values for such methods, the much more simplified admiralty coefficient method is preferred in this study.

The admiralty coefficient method is used in the preliminary design stages to estimate the required power for different sailing speeds. The method calculates the admiralty coefficient (C_A) according to Equation (7.3), with use of displacement (Δ), ship speed (v_s), and shaft power (P_s). This coefficient has similar values for vessels similar in type, displacement, power, and speed. Because the concept is tested for actual designed yachts, the actual original displacement (Δ_1) and speed-power curves are known (P_{s_1}). Accordingly, their corresponding admiralty coefficient can be calculated. After the yacht is weighted with the battery and the displacement is adjusted (Δ_2), this figure is then used in Equation (7.4) to determine the adjusted required shaft powers (P_{s_2}). This results in a modified speed-power curve, specific to a yacht and AER-version.

$$\Delta_2 = (1 + WS_{addition}) \cdot \Delta_1 \tag{7.2}$$

$$C_A = \frac{\Delta_1^{2/3} \cdot v_s^3}{P_{s_1}} \tag{7.3}$$

$$P_{s_2} = \frac{\Delta_2^{2/3} \cdot v_s^3}{C_A} \tag{7.4}$$

This information is used as feedback to the power determination blocks, as it influences the propulsive power at cruise and maximum speeds. This subsequently has an influence on the required size of the generators and auxiliary equipment.

7.5. Equipment scaling

The configurations consist primarily of a battery as ESS and a generator set, but auxiliary equipment must also be considered. This equipment, such as cooling, scales with the installed battery capacity, while generators, switchboards, and converters scale with the required power. Section 7.1 discusses that the generators must be of such power that they can deliver exactly the required power at the cruising speed of the specific concept version. This includes propulsion and hotel power.

The generators are scaled with use of the adjusted speed power curves and according to the power densities as determined in Appendix B. This yields a new weight and volume of the generator set. A converter is required to convert the generated electrical current into the required DC voltage for which the installed switchboard is designed. The switchboard is designed to withstand the maximum amount of electric power indicated by the load balance, thus the combined maximum propulsive plus hotel power. In addition to the switchboard present in an DE-configuration, a component is required to control the battery. Only this part of this switchboard is scaled. Additional service spaces must be taken into account, as the equipment must be able to be maintained and/or operated by the crew.

The battery is scaled according to the energy densities and packing factors, as determined in Appendix C. This packing factor includes the cooling equipment, which is installed capacity dependent, and the additional service spaces of the battery. According to the manufacturer, no additional ventilation is required.

This results in added weight and absorbed volume by the equipment of the configuration, combined with the total installed energy storage capacity of the battery (E_{batt}).

$$m_{batt} = m_{avail} - m_{equip} \tag{7.5}$$

$$E_{batt} = m_{batt} \cdot \rho_{batt} \tag{7.6}$$

7.6. Autonomy determination

This installed energy storage capacity is used to power the yacht during a trip. The exact autonomy of the concept is entirely dependent on the actual operational usage of the yacht. To take this into account, the following three conditions are set at which the AER is determined:

1. The trip is sailed in sea trial state.
2. The trip is sailed at a constant cruising speed.
3. The trip is sailed in constant Mediterranean weather conditions.

The first condition yields that the speed-power curves of sea trials are valid. The supplied curves state the shaft power (P_s) over ship speed relation (v_s). This is transformed to a required electrical energy demand ($\dot{E}$) after the energy source, i.e., either the generator set or the battery. The efficiencies shown in Figure 7.2 are used for this calculation, resulting in an electrical-mechanical efficiency (η_{EM}) of 93.6%. By not including the difference in electric-mechanical efficiency over the course of varying powers, a simplification has been implemented in this calculation. The gearbox efficiency is absent, because it is an electrical configuration and there is no need to install a gearbox.

$$\eta_{EM} = \eta_{fc} \cdot \eta_{swbd} \cdot \eta_{fi} \cdot \eta_{em} \tag{7.7}$$

$$\dot{E}_{prop} = \frac{P_s}{\eta_{EM}} \tag{7.8}$$

The second condition leads to a constant required propulsive power during a trip and thus to a constant required electrical energy consumption of the motor. It is decided to use the waterline length-cruising speed approximation of the WRF described in Chapter 2, after reviewing the data discussed in Chapter 5.

$$F_n = 0.3385 - 0.0011 \cdot L_{wl}$$
$$v_{cruise} = F_n \cdot \sqrt{g \cdot L_{wl}}$$

The third condition causes an assumed constant required hotel power during a trip, hence a constant required electric energy consumption for hotel loads. HVAC loads take up almost half of the hotel load, the remainder hotel loads are also assumed constant. As the weather conditions differ around the globe, a single area is chosen to have stable conditions. The Mediterranean Sea is again chosen as the considered area, as this is where yachts reside the most and the best shore powers are available. Hotel power demand is transformed into a required electrical energy demand with the use of the electrical-electrical efficiency (η_{EE}). The efficiencies shown in Figure 7.2 are used for this calculation, resulting in an electrical-electrical efficiency of 96.5%.

$$\eta_{EE} = \eta_{fc} \cdot \eta_{swbd} \cdot \eta_{fi} \tag{7.9}$$

$$\dot{E}_{hotel} = \frac{P_{hotel}}{\eta_{EE}} \tag{7.10}$$

The total electrical energy consumption during a trip is the summation of both propulsion and hotel values.

$$\begin{aligned} \dot{E}_{tot} &= \frac{P_s}{\eta_{EM}} + \frac{P_{hotel}}{\eta_{EE}} \\ &= \dot{E}_{prop} + \dot{E}_{hotel} \end{aligned} \tag{7.11}$$

With the maximum installed electrical capacity on-board determined in Equation (7.6), the time for which the configuration is able to power the yacht fully electrical can be calculated. This is autonomy is split into two all-electric times ($AETs$): the AET_{hotel} and AET_{cruise}. The AET_{hotel} is the time the batteries can power the hotel operation of a yacht when anchored. The AET_{cruise} is the time the batteries can power the hotel plus the propulsive operation of a yacht during a cruise at the design cruise speed. Subsequently, this AET_{cruise} is used in combination with the defined design cruising speed to determine the all-electric range (AER).

$$AET_{hotel} = \frac{E_{batt}}{\dot{E}_{hotel}} \tag{7.12}$$

$$AET_{cruise} = \frac{E_{batt}}{\dot{E}_{tot}} \tag{7.13}$$

$$AER = v_{cruise} \cdot AET_{cruise} \tag{7.14}$$

8

Parametric concept design

In this chapter, the method explained in Chapter 7 is used to generate the parametric concept designs. The compensation weight is determined in Section 8.1, then the speed-power curves are adjusted in Section 8.2 to scale the equipment in Section 8.3. The resulting autonomy per version is presented in Section 8.4.

In total, nine parametric conceptual designs are created and examined in this study. Among these nine designs, a subdivision was made into autonomy and yacht waterline length, see Table 8.1. There are three different autonomy versions of the concept depending on the weight-share addition for each length category of yachts. This is shown in the last column. The designs of the concept versions are a parametric design, indicating the size and volume of the equipment according to their autonomy.

Table 8.1: The nine different to be designed concept versions.

Concept version	**Size category (L_{wl})**	**Autonomy version**	**Weight-share addition**
v1-S	Up to 50m	Short	0.0%
v2-S	Up to 50m	Mid	2.5%
v3-S	Up to 50m	Long	5.0%
v4-M	50-80m	Short	0.0%
v5-M	50-80m	Mid	2.5%
v6-M	50-80m	Long	5.0%
v7-L	80m and above	Short	0.0%
v8-L	80m and above	Mid	2.5%
v9-L	80m and above	Long	5.0%

8.1. Available compensation weight

As a start, the available compensation weight by decreasing the generators is calculated. This is different per yacht and size category, therefore the benchmark yachts are considered in order to obtain actual values. First, it is checked if all the benchmark yachts have a DE-configuration installed. This is not the case. Yacht-M has a DD-configuration installed. This is taken into account by removing a total $31.5t$ for steering equipment and propeller. It is replaced with a $4000kW$ thruster, weighing around $42.4t$ including the additional equipment. The determination of the available compensation weight by decreasing the generators is provided in Table 8.2. Note that the new generators and auxiliary equipment are yet to be scaled.

As second, the available compensation weight by optimising tank usage according to the aforementioned method is determined. MGO is used as fuel oil ($0.000860t/ltr$) and kerosene as helicopter fuel ($0.000804t/ltr$) [59]. The different weights of the tanks in different operating conditions are shown in Table 8.3-8.5. Yacht-S has the smallest difference between installed and crossing capacity, yielding a $5.9t$ available weight for compensation. Yacht-M has the smallest difference between installed and guest capacity, yielding a $28.4t$ available weight for compensation. Yacht-L has the smallest difference between installed and crossing stay capacity, yielding a $89.8t$ available weight for compensation.

Table 8.2: The available compensation weight by decreasing generators.

Component	**Yacht-S** [t]	**Yacht-M** [t]	**Yacht-L** [t]
ME	9.7	21.5	72.5
Auxiliary generator/ESS	5.6	11.6	14.4
Gearbox	0.0	5.8	21.3
DD-DE compensation	0.0	-10.9	0.0
Total	**15.3**	**28.0**	**108.2**

Table 8.3: The available compensation weight by optimising tank usage for Yacht-S.

Tank	**Tank capacity**	**Filling**	
	Installed [t]	Guest stay [t]	Crossing [t]
Fuel oil (MGO)	26.0	19.5	26.0
Fresh water	4.9	4.9	1.5
Heli fuel (Kerosine)	0.0	0.0	0.0
Pool	2.5	2.5	0.0
Total	**33.3**	26.9	**27.4**

Table 8.4: The available compensation weight by optimising tank usage for Yacht-M.

Tank	**Tank capacity**	**Filling**	
	Installed [t]	Guest stay [t]	Crossing [t]
Fuel oil (MGO)	113.5	85.1	113.5
Fresh water	33.2	33.2	10.0
Heli fuel (Kerosene)	0.0	0.0	0.0
Pool	20.8	20.8	0.0
Total	**167.5**	**139.1**	123.5

Table 8.5: The available compensation weight by optimising tank usage for Yacht-L.

Tank	**Tank capacity**	**Filling**	
	Installed [t]	Guest stay [t]	Crossing [t]
Fuel oil (MGO)	360.3	270.2	360.3
Fresh water	97.1	97.1	29.1
Heli fuel (Kerosene)	8.6	8.6	0.0
Pool	13.2	13.2	0.0
Total	**479.2**	389.1	**389.4**

Before the equipment is scaled, the third method to add weight on board is applied - The increase of displacement according to the weight-share addition of the versions as stated in Table 8.1. This increase in displacement is bound by the 5% design limitation. The sum of the three methods results in the total available weight for compensation. These weights differ significantly per version of the concept, as shown in Table 8.6.

Table 8.6: The total available weight for compensation.

Compensation weight	Yacht-S			Yacht-M			Yacht-L		
	0.0%	2.5%	5.0%	0.0%	2.5%	5.0%	0.0%	2.5%	5.0%
	[t]	[t]	[t]	[t]	[t]	[t]	[t]	[t]	[t]
Decreasing generators	15.3	15.3	15.3	28.0	28.0	28.0	108.2	108.2	108.2
Optimising tank usage	5.9	5.9	5.9	28.4	28.4	28.4	89.8	89.8	89.8
Weight-share addition	0.0	9.0	18.1	0.0	33.0	65.9	0.0	84.8	169.5
Total	**21.2**	**30.2**	**39.3**	**56.4**	**89.4**	**122.3**	**198.0**	**282.8**	**367.5**

8.2. Adjustment speed-power curves

The weight-share addition per version causes for a difference in propulsive power required per version. To determine this increase in power, the admiralty coefficient method is applied, as explained in Section 7.4. The increase in weight-share is the only added weight with respect to the sea trial displacement of the yacht. Therefore, the new displacement of the concept version can be determined directly, hence the adjusted speed-power curve. These adjusted curves are depicted in Appendix E.

In order to scale the generators to the required power, the cruising speed is first determined. As mentioned earlier, this speed is determined according to the length-speed relation of Equation 2.1 resolved by theWater Revolution Foundation. Using the corresponding adjusted speed-power curve, this yields the required shaft powers, as shown in Table 8.7.

Table 8.7: The estimated cruising speeds of the different sized yachts, resulting in the required shaft powers.

Concept version	Length	Speed				Power	
	L_{wl}	F_n	v_{cruise}		v_{max}	$P_{s,cruise}$	$P_{s,max}$
	[m]	[-]	[m/s]	[kts]	[kts]	[kW]	[kW]
v1-S	45	0.29	6.07	11.8	17.0	313.8	1759
v2-S	45	0.29	6.07	11.8	17.0	319.0	1789
v3-S	45	0.29	6.07	11.8	17.0	324.2	1818
v4-M	75	0.26	6.94	13.5	18.5	1209	3294
v5-M	75	0.26	6.94	13.5	18.5	1229	3349
v6-M	75	0.26	6.94	13.5	18.5	1249	3403
v7-L	100	0.23	7.16	13.9	18.5	2562	6582
v8-L	100	0.23	7.16	13.9	18.5	2605	6691
v9-L	100	0.23	7.16	13.9	18.5	2647	6799

8.3. Equipment scaling

This available weight is the design freedom of the concept version. The battery, generators, and auxiliary equipment are scaled to take up all this weight. This is done by first scaling the generators and auxiliary equipment per version to the required size and then scaling the battery to the remaining weight. Using the feedback from the previous section, the propulsion power at cruising speed for scaling the generators is determined, as shown in Table 8.8. The auxiliary equipment must be able to cope with the required maximum power. Therefore, the shaft powers at maximum speed are also determined. In addition to the loads associated with propulsion operations, the loads associated with hotel operations increase the total power. The hotel loads are yacht size specific. They are listed together with the totals in the last columns of Table 8.8.

Table 8.8: The resulting required shaft powers, related hotel loads and summed total loads at the energy sources ($\dot{E}$).

Concept version	**Shaft power**		**Hotel power**	**Total power**	
	$P_{s,cruise}$ [kW]	$P_{s,max}$ [kW]	P_{hotel} [kW]	$P_{t,cruise}$ [kW]	$P_{t,max}$ [kW]
v1-S	313.8	1759	65.0	402.5	1946
v2-S	319.0	1789	65.0	408.0	1977
v3-S	324.2	1818	65.0	413.5	2008
v4-M	1209	3294	180	1478	3704
v5-M	1229	3349	180	1499	3763
v6-M	1249	3403	180	1520	3820
v7-L	2562	6582	400	3151	7443
v8-L	2605	6691	400	3196	7560
v9-L	2647	6799	400	3241	7676

With the required powers known, the generator sets and corresponding auxiliary equipment can be scaled. Their design parameters are determined in Appendix B, and are the following: The gravimetric power density of the generator sets ($\rho_{g,gens}$) is $106 ekW/t$ and has a determined density (ρ_{gens}) of $0.67 t/m^3$. The corresponding weight ($\rho_{g,aux}$) and volume ($\rho_{V,aux}$) of the power dependent auxiliary equipment and service spaces are taken into account with the determined values of $0.00171 t/ekW$ and $0.00565 m^3/ekW$.

$$m_{gens} = \frac{P_{tot,cruise}}{\rho_{g,gens}} \tag{8.1}$$

$$V_{gens} = \frac{m_{gens}}{\rho_{gens}} \tag{8.2}$$

$$m_{aux} = P_{tot,max} \cdot \rho_{g,aux} \tag{8.3}$$

$$V_{aux} = P_{tot,max} \cdot \rho_{V,aux} \tag{8.4}$$

The remainder of the available weight is available for the battery and associated cooling equipment. This therefore indicates the installed capacity per concept version. These design parameters are determined in Appendix C, and take the depth-of-discharge (DoD) of 75% and an end-of-life (EoL) of 90% of the battery into account. As a result, the energy densities shown are the usable energies of the battery. The resulting parameters are the following: The gravimetric energy density of the battery ($\rho_{g,batt}$) is $124 kWh/t$, with a volumetric energy density ($\rho_{V,batt}$) of $183 kWh/m^3$. The corresponding weight and volume of the auxiliary equipment of the battery and service spaces are taken into account by dividing both densities of the battery with the corresponding dimensionless packing factors (PF) - 1.004 for weight and 1.203 for volume. This packing factor takes the service spaces and cooling equipment for the batteries into account.

$$m_{batt} = m_{avail} - m_{gens} - m_{gens,aux} \tag{8.5}$$

$$E_{batt} = m_{batt} \cdot \frac{\rho_{g,batt}}{PF_m} \tag{8.6}$$

$$V_{batt} = \frac{E_{batt}}{\left(\frac{\rho_{V,batt}}{PF_V}\right)} \tag{8.7}$$

Combining these densities with the previously determined values for available compensation weight and required power yields the mass and volume sizes of the various concept versions shown in Table 8.9. The battery capacity shown is the total usable capacity of the installed battery. This takes into account the DoD of 75% and an EOL of 90% of the battery. These parameters have been incorporated into the energy density of the battery. Therefore, the actual installed battery capacity of the concept versions are higher by a factor of 1.48.

Table 8.9: The mass and volume parameters of the designed concept versions, and corresponding installed battery capacity.

Concept version	Mass available	Generators		Auxiliary equipment		Battery			Configuration	
	Mass [t]	Mass [t]	Volume [m^3]	Mass [t]	Volume [m^3]	Mass [t]	Volume [m^3]	Capacity [kWh]	Mass [t]	Volume [m^3]
v1-S	21.2	3.80	5.67	3.33	11.0	14.0	11.4	1736	21.2	28.1
v2-S	30.3	3.85	5.75	3.38	11.2	23.0	18.6	2836	30.3	35.5
v3-S	39.3	3.90	5.82	3.43	11.3	32.0	25.9	3937	39.3	43.0
v4-M	56.4	13.9	20.8	6.33	20.9	36.1	29.2	4446	56.4	70.9
v5-M	89.3	14.1	21.1	6.43	21.3	68.8	55.6	8467	89.3	98.0
v6-M	122	14.3	21.4	6.53	21.6	101	82.0	12487	122	125
v7-L	198	29.7	44.4	12.7	42.1	156	126	19151	198	212
v8-L	283	30.2	45.0	12.9	42.7	240	194	29510	283	282
v9-L	368	30.6	45.6	13.1	43.4	324	262	39870	368	351

8.4. Autonomy determination

Dividing the installed usable capacity of the battery with the energy consumption during a trip according to the defined conditions, results in the AET. This defines the time the yacht is able to sail all-electric, thus without switching on her generators to power the yacht. Multiplying this AET by the cruising speed at which the trip is sailed, results in the AER the concept is able to sail. These characteristics are summarised in Table 8.10.

The results show that the $AETs_{hotel}$ are all of a very significant length. They are longer than a complete day, and even increase up to more than four days in the largest concept version. During this time, the generator sets do not have to be started.

Furthermore, all concept versions are able to sail multiple hours powered by batteries. These $AETs_{cruise}$ are all longer than the mode of the trip duration, 3.0 hours, presented in Figure 5.9. They range from several hours, to an estimated complete cruising day of more than 8 hours, when battery capacity increases throughout the concept versions.

Additionally, the results show that the concept with the largest range is able to sail a trip from Antibes to Livorno fully electric, or the concept version with the smallest range from Nice to Saint-Tropez. These full electric trips range from $40nm$ to $171nm$ among the concept version. This fits within the defined trip distance range between the mode and the mean, $25nm$ to $200nm$, as presented in Figure 5.7.

Table 8.10: A summary of the design characteristics of the concept versions.

Concept version	Configuration		Powers		Capacity Battery		All-electric		
	Mass [t]	Volume [m^3]	Cruise [kW]	Maximum [kW]	Installed [kWh]	Usable [kWh]	AET_{hotel} [hrs]	AET_{cruise} [hrs]	AER [nm]
v1-S	21.2	28.1	402.5	1946	2571	1736	26.7	4.3	50.9
v2-S	30.3	35.5	408.0	1977	4202	2836	43.6	7.0	82.0
v3-S	39.3	43.0	413.5	2008	5833	3937	60.6	9.5	112
v4-M	56.4	70.9	1478	3704	6587	4446	24.7	3.0	40.6
v5-M	89.3	98.0	1499	3763	12543	8467	47.0	5.6	76.3
v6-M	122	125	1520	3820	18500	12487	69.4	8.2	111
v7-L	198	212	3151	7443	28372	19151	47.9	6.1	84.5
v8-L	283	282	3196	7560	43719	29510	73.8	9.2	128
v9-L	368	351	3241	7676	59067	39870	99.7	12	171

IV

Effects & Debrief

9 Potential Impacts

The effectiveness of the different concept versions designed in Chapter 8 is measured using the fleet utilisation factor (UF). The UF method is explained in Section 9.2. This UF is used as a basis in Section 9.3 to 9.5 to determine whether the defined impact objectives of this study in terms of sustainability, comfort, and operations are achieved, but first the impact on yacht design is determined in Section 9.1.

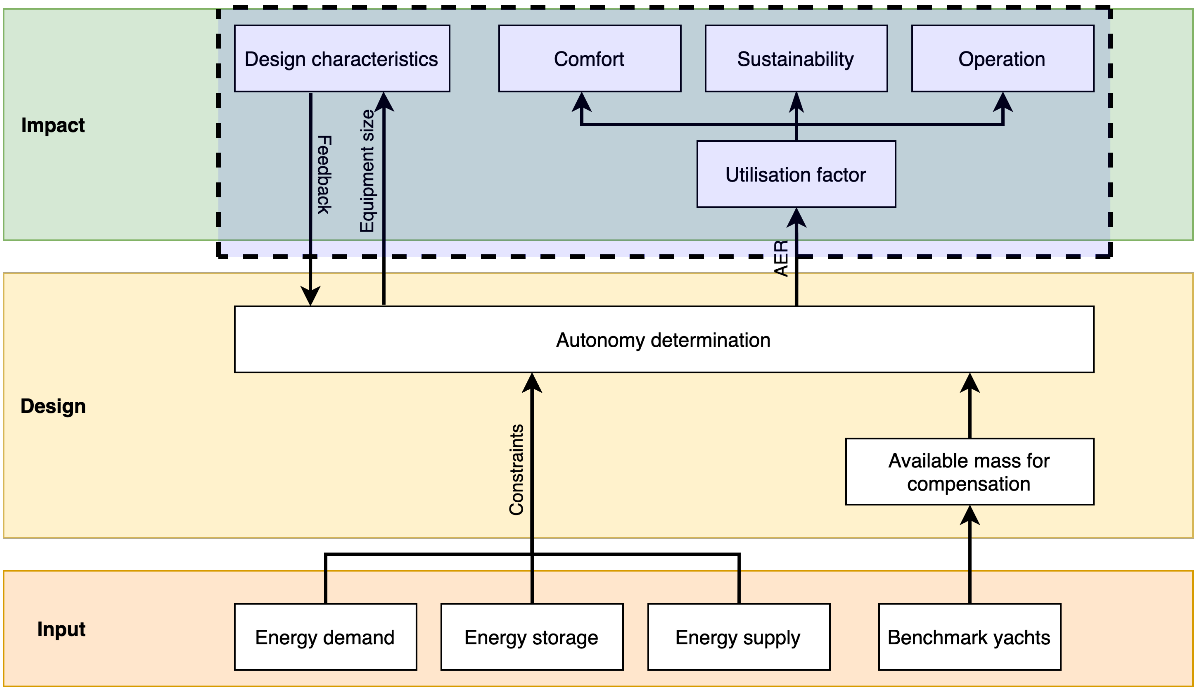


Figure 9.1: The design process flowchart, with the impact part highlighted.

9.1. Impact on design

Equipment of an electric configuration can be freely placed within a yacht, as the power transmission is electrical rather than mechanical. Therefore, added batteries and auxiliary equipment can be freely placed. The main consequence is the additional displacement and absorbed space on board. The effect of the additional displacement is already adjusted for in Section 8.2, but the effect on the general arrangement is unknown.

- The contribution of the configuration to the mass of the ship is called the weight-share (WS). The impact on design is quantified by determining the additional mass of the concept compared to the displacement. The additional mass was bound by design criteria and used as a scaling parameter of the concept, therefore the influence of the mass on the design of the versions is directly known.

$$WS = \frac{m_{conf}}{\Delta} \tag{9.1}$$

$$WS_{added} = \frac{m_{conf,added}}{\Delta} \tag{9.2}$$

- The volume absorbed by the configuration of the ship's volume is called the volume-share (VS). The effect on the design is quantified by determining the additional volume absorbed by the configuration compared to the volume of the yacht. However, two challenges arise: The volume of the yacht is presented in Gross Tonnage and the original volume of the benchmark configuration is unknown. This makes it impossible to determine the additional absorbed volume.

$$VS = \frac{V_{conf}}{V_{yacht}} \tag{9.3}$$

$$VS_{added} = \frac{V_{conf,added}}{V_{yacht}} \tag{9.4}$$

The first challenge is resolved by converting the yacht's gross tonnage to cubic meters, using the relationship defined in Regulation 3 of Annex 1 of The International Convention on Tonnage Measurement of Ships [27]. The inverse of this relation can only be calculated approximately, since the logarithm is present in the denominator when the equation is inverted. Therefore, the relation is plotted and the cubic meter volumes of the yachts are approximated, see Figure 9.2. The figure shows the three benchmark yachts considered.

$$K = 0.2 + 0.02 \cdot \log_{10}(V) \tag{9.5}$$

$$GT = K \cdot V \tag{9.6}$$

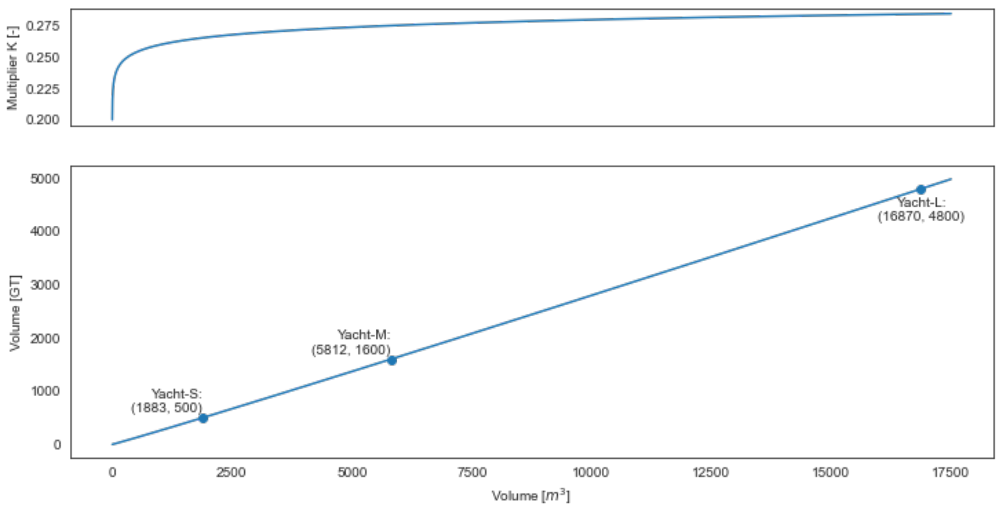


Figure 9.2: The gross tonnage relation according to Regulation 3 of Annex 1 of The International Convention on Tonnage Measurement of Ships [27].

The second challenge is solved by careful consideration of the concept-specific equipment shown in Figure 7.2. The battery, the associated inverter, and the switchboard equipment specific to controlling the batteries are added to the configuration. This results in only the generator being rescaled when converting from the benchmark DE configuration to the new concept under study. The volume of the new configuration is already determined, so the original size of the generator set must be subtracted from it to determine the added volume.

$$V_{conf,added} = V_{conf} - V_{gens,original} \tag{9.7}$$

To determine the original size, the previously determined regression parameters are used in combination with the originally installed generator power. This provides an indication of the volume of generator sets originally installed. The determined values can be found in Table 9.1. This is then used to determine the additional absorbed volume of the plug-in concept.

$$m_{gens,original} = \frac{P_{installed}}{\rho_{g,gens}} \tag{9.8}$$

$$V_{gens,original} = \frac{m_{gens,original}}{\rho_{gens}} \tag{9.9}$$

Table 9.1: The estimated original generator set size specific to the three benchmark yachts.

Yacht	**Original installed power** $[kWe]$	**Estimated original generator set size** $[m^3]$
Yacht-S	2250	31.7
Yacht-M	4500	63.4
Yacht-L	10500	148

The resulting impact on the design of a yacht is shown in Table 9.2. The results show that the added weight-share is small and within the specified design limits, but the absolute numbers increase significantly as the yachts become larger. The difference between the total weight-share and added weight-share ranges from 4.3% to 5.9% for the benchmark yachts, resulting in total weight-shares of up to 11%. Yachts-S and Yacht-L have similar trends in total weight-share, while Yacht-M has a lower share. It is expected that this can be attributed to the fact that Yacht-M was not originally installed with a DE propulsion system. Therefore, similar shares can be expected if a medium size yacht is originally equipped with a DE propulsion system.

The effect of reducing the size of the generator sets is clearly visible. For the smallest concept variant, there is even a small unused volume, although this is probably not reflected in the design. Furthermore, the volume-share on top of the concept's additional volume decreases across the three different benchmark yachts. This ranges from 1.7% (1.5% + 0.2%) for Yacht-S, to 1.1% (1.2% − 0.1%) for Yacht-M, and to 0.9% (1.3% − 0.4%) for Yacht-L. This can be attributed to the effect explained in the last paragraph of Section3.3.1, where it is stated that the propulsion system occupies a larger volume fraction in smaller yachts. Therefore, reducing the size of the generators leads to a more pronounced effect.

The resulting additional volumes do not clearly visualise how this affects the actual space available on a yacht. By using an average ceiling height of a yacht of $2.1m$ an indication can be given. Only the largest concept versions of the benchmark yachts are considered, i.e. concept versions 3, 6, and 9. Concept version 3 takes up an additional $11.3m^3$. This is an area of about $5m^2$, which is roughly equivalent to a small on-board storage room or a single guest day head. For the medium and large yachts, this area increases significantly to $30m^2$ and $100m^2$ respectively. For Yacht-M, this is equivalent to the on-board spa or a single guest bathroom. For Yacht-L, this corresponds to the on-board cinema, a complete guest cabin including bathroom, or a large portion of the tender storage area. These larger areas can of course also be made up of several smaller rooms. A visualisation of concept version 6 can be found in Figure 9.3. Only the concept specific equipment is shown.

9.2. Utilisation Factor

To measure the impact of a concept version with a specific AER, the fleet Utilisation Factor (UF) is used, as explained in Section 3.2. The UF of the fleet is defined as the ratio between the cumulative distance sailed in the charge depletion mode (CD-mode), and the summed total distance sailed. In this study, the UF averaged over the fleet is used as an indication of the actual resulting UF of a single concept version.

$$UF = \frac{\sum d_{CD}}{\sum d_{total}} \tag{9.10}$$

To obtain the required values, the AIS dataset from chapter 5 is again used. The individual trip distances are split into a fossil fuel and an electric distance. It is assumed that each recorded trip had the possibility to be started with a fully charged battery. This indicates that every trip starts and ends in a marina with a

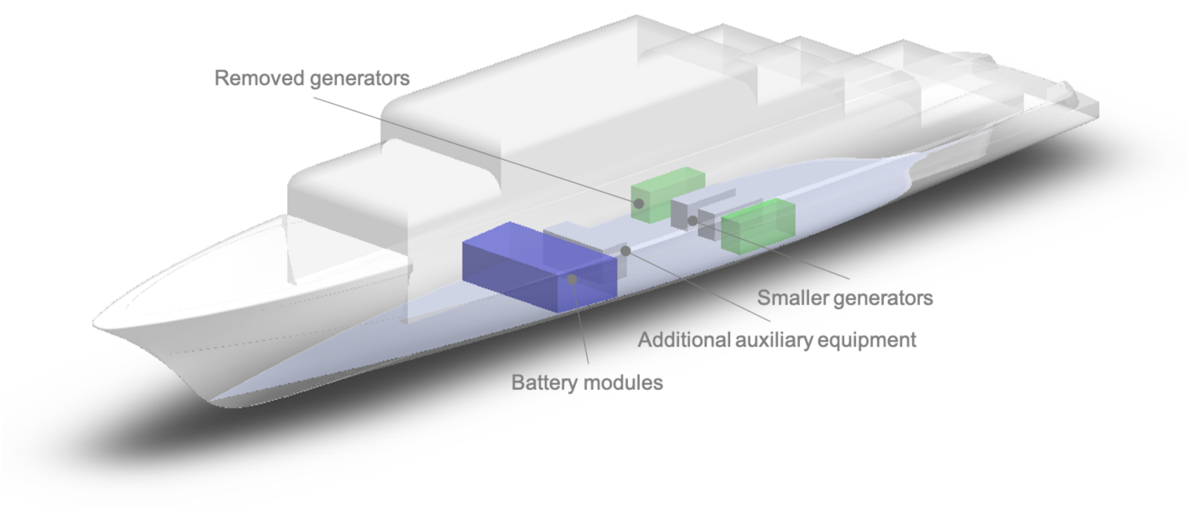


Figure 9.3: Concept version 6 implemented in the corresponding benchmark Yacht-M.

shore power infrastructure that meets the required levels. Thus, there is an assumption in this calculation that results in the calculated UF being only the theoretical maximum possible UF.

This electric range is the minimum of either the AER or the trip distance. The remainder is defined as the fossil fuel distance. All individual all-electric distances are summed to obtain the total electric distance. This is divided by the sum of the total sailed distance to obtain the UF of the concept version.

$$d_{CD} = min\left(AER, d_{trip}\right) \tag{9.11}$$

The UF is 1.0 up to the AER, from which point it decreases to a final total value equal to the resulting impact on total sailed nautical miles. This impact is defined as the theoretical maximum feasible fraction of the total distance that can be sailed all-electric. It takes into account the electric fraction of the trips sailed over a distance greater than the AER, i.e. the cumulative effect of sailing, say, $50nm$ fully electric on a $100nm$ trip. The effect over the entire trip distance spectrum is calculated by multiplying the UF with the fraction of the total distance sailed. This fraction is the distance line in the CDF diagram.

$$Impact_{distance} = UF \cdot CDF_{distance} \tag{9.12}$$

This principle is best explained by an example. Recall Figure 5.8, where both the occurrence and the distance lines are shown in a CDF diagram. For this example, a configuration with an AER of exactly $150nm$ - the maximum estimated guest trip - is installed. See Figure 9.4 for the progression of the resulting impacts. The impact on the number of all-electric trips is determined up to the last point where the UF is 1.0, equal to an

Table 9.2: The impact of the concept versions on yacht design.

Concept version	**Weight-share**				**Volume-share**			
	Added		Total		Added		Total	
	[t]	[%]	[t]	[%]	$[m^3]$	[%]	$[m^3]$	[%]
v1-S	0.00	0.0	21.2	5.9	-3.60	-0.2	28.1	1.5
v2-S	9.04	2.5	30.2	8.4	3.80	0.2	35.5	1.9
v3-S	18.1	5.0	39.3	11	11.3	0.6	43.0	2.2
v4-M	0.00	0.0	56.4	4.3	7.50	0.1	70.9	1.2
v5-M	33.0	2.5	89.4	6.8	34.6	0.6	98.0	1.7
v6-M	65.9	5.0	122	9.3	61.6	1.1	125	2.2
v7-L	0.00	0.0	198	5.8	64.0	0.4	212	1.3
v8-L	84.8	2.5	283	8.3	134	0.8	282	1.7
v9-L	170	5.0	368	11	203	1.2	351	2.1

impact of almost 75%. Up to this point, all trips are fully electric. Since each trip is started with a fully charged battery, trips with a distance greater than the AER are also partially all-electric. This results in any trip greater than AER having a continuous effect on the all-electric nautical miles. Therefore, the utility of the concept decreases slightly after this point. This is indicated by the decreasing UF. This cumulative effect adds up to more than 35% in this example - the maximum theoretically possible share.

The progression of both impact values over an increasing AER to the estimated maximum distance sailed with guests is shown in Figure 9.5. These show a maximum achievable value for guest trips corresponding to the impact values of the example above.

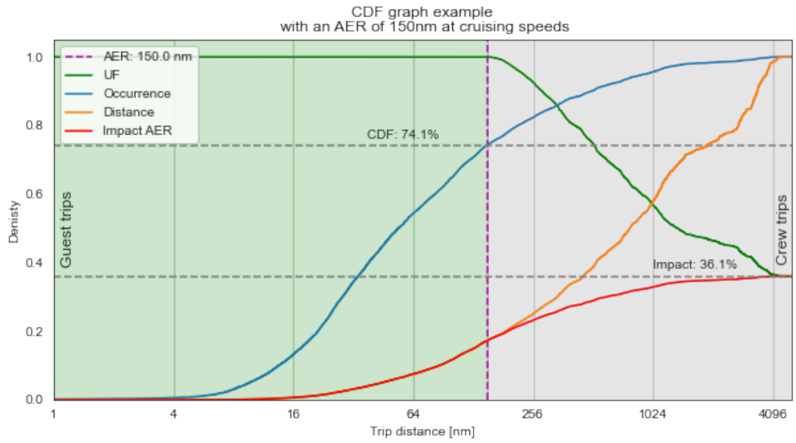


Figure 9.4: An example CDF diagram showing the impact on number of trips sailed and total sailed distance for an AER of exactly 150nm.

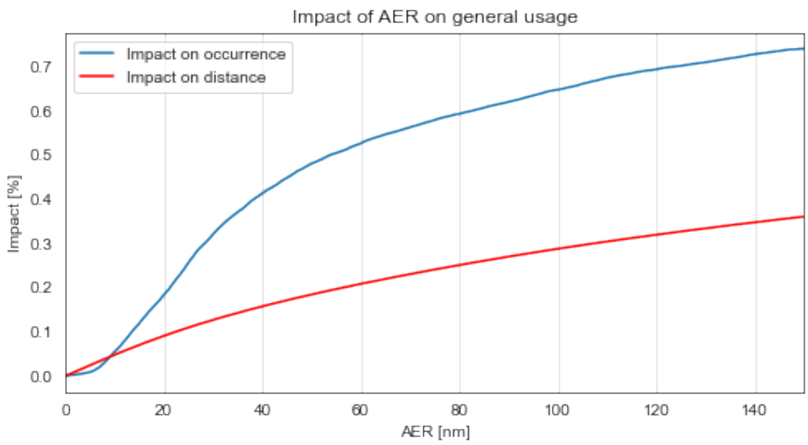


Figure 9.5: The effect of an AER in relation to the general operation of a yacht with guests on board.

All designs of the concept versions have their design-specific AER, i.e. different associated CDF diagrams. All these version-specific CDF diagrams are shown in Appendix E. They show that the impact of an AER on the total sailed electrical distance is significant for trips larger than the AER for all versions. These version-specific impacts are shown in Table 9.3.

These considerable impacts on usage are achieved with sailing only a small fraction of the full range capability on battery power. On average, the full range of superyachts is about 5000 nautical miles, so these effects are achieved at only about 2% to 3% of this full range. This highly underlines the potential of whatever hybrid concept in the yachting industry. This also confirms the expectation that sailing only a portion of the total range on battery power can result in a large effect.

Furthermore, within occurrence impact, a distinction is made between overall and guest usage. This distinction is made because guests are not on board for all trips. In Section 5.2.2, it was estimated that the maximum guest trip has a range of approximately $150nm$. Although no data on guest presence is available, this is considered a good estimate. Trips up to this range account for nearly 75% of the trips. The fact that this represents only three quarters of the total number of trips suggests that guests are experiencing a higher proportion of trips sailed purely on electric power.

Table 9.3: The utilisation impact on overall usage, plus the impact on occurrence-share limited to guest usage.

Concept version	**All-electric**		**Impact overall usage**		**Impact guest usage**
	Time [hrs]	Range [nm]	Occurrence [%]	Distance [%]	Occurrence [%]
v1-S	4.3	50.9	48.5	18.7	65.5
v2-S	7.0	82.0	59.9	25.5	80.8
v3-S	9.5	112	68.0	30.8	91.8
v4-M	3.0	40.6	41.8	15.9	56.4
v5-M	5.6	76.3	58.4	24.4	78.8
v6-M	8.2	111	67.7	30.6	91.4
v7-L	6.1	84.5	60.6	26.0	81.7
v8-L	9.2	128	70.8	33.2	95.5
v9-L	12	171	76.2	38.6	103

9.3. Impact on sustainability

The objective of this study is to increase the annual sustainability level of a yacht by 10% compared to the benchmark, measured in global warming potential (GWP). A life cycle assessment (LCA) is performed to determine the difference in emissions between the plug-in hybrid electric concept and the diesel-electric benchmark concept. To determine the difference in emissions, only the difference between the two configurations needs to be examined.

- The additional emissions from the production of the batteries. These are determined via a cradle-to-gate (CTG) analysis - GWP up to the gate of the factory. This is made up of the mining emissions from the materials used plus the emissions from the electricity used in production. The effect of recycling the batteries or giving them a second life are also important factors to consider.
- The operational emissions saved by partially shifting from MGO to the electricity grid as an energy source. This is associated with an expected reduced GWP of the electricity grid compared to the combustion of MGO. These emissions are determined via a well-to-wake (WTW) analysis - GWP up to the wake of the vessel. This is composed of extraction, production, refinery, and transport emissions up to the on-board tank in the well-to-tank (WTT) phase and combustion emissions within the ship from the tank to the wake in the tank-to-wake (TTW) phase. The difference in emissions due to downsizing of the generators is neglected.

The sustainability impact is quantified by determining the number of cycles required to offset the battery's production emissions, referred to as the number of compensation cycles. The result is completely dependent on the input parameters determined, therefore the results may vary significantly when different parameters are chosen. Due to the increasing development of batteries and the increasing renewable power grid, it is expected that all related parameters will change in the near future.

$$\text{Compensation cycles} = \frac{\text{Battery production GWP}}{\text{MGO GWP} - \text{Electric grid GWP}} \tag{9.13}$$

9.3.1. Cradle-to-Gate analysis

Since the environmental impact of lithium-ion battery production has sparked debates in society, awareness has increased worldwide and numerous studies have been conducted on the subject. In this study, four studies on battery production emissions using the cradle-to-gate principle are examined.

1. The most comprehensive study conducted is that of Peters et al. [45], which reviewed 79 LCA studies, of which 24 used the GWP. Almost all based their results on an EU or US energy mix. They concluded that the average total GWP of manufacturing a battery is 110 kg CO_2-eq/kWh. However, this is an average across all battery types, so a subdivision was made. Section 2.5 shows that the NCA and NMC structures have the highest potential for use in the studied concept. The reviewed study concludes that these have a production GWP of 116 kg CO_2-eq/kWh and 160 kg CO_2-eq/kWh respectively.
2. Ellingsen et al. [10] conducted a LCA study on lithium-ion battery vehicle packs and compared their results with six other studies. They concluded that lithium-ion batteries, when manufactured in large production quantities, have a GWP of 172 kg CO_2-eq/kWh, which is within the range of 53 to 338 kg CO_2-eq/kWh of the previous six studies they examined.
3. The third study examined is that of Kim et al. [33]. They examined the impact of the production of the lithium-ion battery of the Ford Focus BEV and came up with a GWP of 140 kg CO_2-eq/kWh.
4. The last study examined is a briefing by Hall [20] for The International Council on Clean Transportation, reviewing eleven studies. They state that the GWP ranges from 56 to 494 kg CO_2-eq/kWh, but consider the value of 175 kg CO_2-eq/kWh to be representative.

Averaging these numbers and combining the NCA and NMC values from the first study yields an average production GWP for lithium-ion batteries of 152.6 kg CO_2-eq/kWh. This figure is a general average that can only be used for an initial estimate of the environmental impact.

One method to get actual GWP values from the manufacturer is to obtain the Environmental Product Declaration (EPD) of their specific battery. Manufacturers such as Volkswagen, Polestar, and Tesla have these available for the batteries used in their products [47, 53, 60]. Unfortunately, this information regarding the considered battery in this concept is not obtained in this study.

The impact of production can be reduced by recycling the used batteries or giving them a second life in another industry, such as an application to increase grid stability. This leads to an increase in the emission reduction potential during the installation on a yacht for only part of its life. These two options are proposed in the study of Hall [20] and discussed below.

- A second life application aims to average out the significant GHG emissions of manufacturing over a longer period of time and distribute the GWP of manufacturing across the many users it has. Neubauer et al. [42] and Kumar et al. [35] predict that an application as a grid peak shaver is feasible and will lead to a GHG emission reduction for society. Since this is a relatively new research topic, specific reduction quantities are not yet available, so they are not provided in this estimate.
- Recycling of batteries is a common practise, including lithium-ion batteries. The reuse of scarce materials ensures that the growing market for lithium-ion batteries retains sufficient resources for key components, but also shows a lower environmental impact due to the elimination of mining emissions. However, Chen et al. [6], Huang et al. [23] and Harper et al. [22] explain that there are different recycling techniques available for each battery type, all with different characteristics, efficiencies and resulting

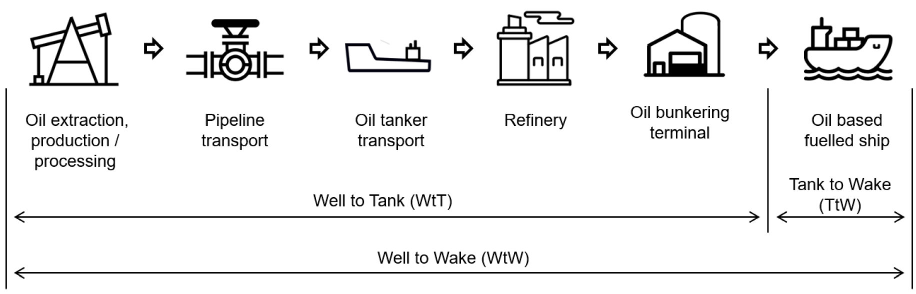


Figure 9.6: An example of the LCA model. The division in the different phases and corresponding emission activities are visualised.[24]

GWP. Currently, none of the available battery recycling technologies are ideal, and challenges still need to be overcome. These can be overcome if an industry standard battery type is chosen so that recycling technologies can specialise in that specific type. However, all battery compositions have different properties that may be important for specific applications. Therefore, a selection between battery types is not expected in the near future. Initial estimates suggest that the potential is significant, but again, no concrete figures are yet available and are therefore not provided in this study.

Thus, only a general indicative estimate of the production GWP of a lithium-ion battery with a value of 152.6 kg CO_2-eq/kWh is available for the present study. However, considering the potential for reuse and recycling and the increasingly renewable production of lithium-ion batteries, this figure is definitely something that should be reconsidered in future studies. Estimated future emission levels from battery production are not studied, as ships built with the plug-in concept in the near future (≤ 5 years) will most likely continue to sail with these batteries in the future (≥ 15 years).

9.3.2. Well-to-Wake analysis

The well-to-wake (WTW) analysis is performed for the two energy sources, MGO and electricity, and consists of two parts: a well-to-tank (WTT) part and a tank-to-wake (TTW) part. This split is made since both energy sources have a different production, plus their efficiencies within the configuration are different.

- The GWP of the WTT phase is determined using previously conducted scientific studies.
- The GWP of the TTW phase is determined using the results of the WTT phase in combination with the efficiencies within the concept configuration.

Figure 9.7 shows the two energy sources used in the plug-in concept, fossil fuels and shore power, being MGO and the power grid respectively. Both the WTT and TTW phases of these two energy sources are different. While MGO is produced remotely and needs to be transported in large quantities to the refuelling site, electricity is often also generated but without transport emissions. Within the concept configuration, the energies encounter different efficiencies, resulting in different local emissions.

The difference in efficiency within the concept is shown in Figure 9.7, where $\dot{Q}_f$ is the heat input of the fossil fuel and $\dot{E}_{SP}$ is the electrical energy input of the shore power. Therefore, emissions can only be compared when there is an equal amount of energy available at the same point in the system. The point under consideration is referred to as point 2 in the figure. At this point, all efficiencies within the system are encountered, except that of the propeller. The propeller efficiencies differ significantly depending on hull and propeller design, neither of which are considered in this study, so the propeller efficiencies are not included. This analysis can therefore also be referred to as a well-to-propeller (WTP) analysis.

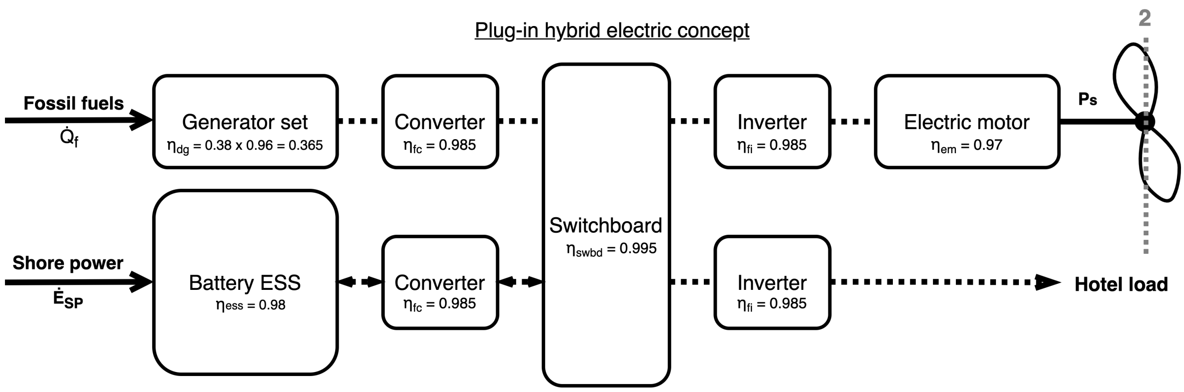


Figure 9.7: Point 2 denoted in the configuration of the plug-in concept.

Fossil fuels The fossil fuel most commonly used in the yachting industry is MGO. The GWP of MGO is defined by the total GHG emissions generated during production and transport in the WTT phase, combined with the GHG emissions generated during combustion of MGO in the TTP phase.

The GWP of MGO in the WTT phase is examined in the study by Verbeek et al. [59]. They concluded that the WTT GHG emissions of MGO are 12.7g CO_2-eq/MJ. This corresponds to 0.046 kg CO_2-eq/kWh, or combined with its characteristic LHV of 42.7 MJ/kg, this corresponds to 0.54 kg CO_2-eq/kg MGO [34].

The GWP of MGO in the TTP phase is calculated with use of the configuration efficiency, the LHV, and the non-dimensional conversion factor (CF) between fuel consumption and CO_2 emissions based on carbon content. The CF is defined to be 3.206 kg-CO_2/kg-MGO in a study of IMO [28]. This is not determined in CO_2-eq but only in CO_2, however, this simplification is deemed viable.

$$\text{GWP MGO TTP} = \frac{CF \cdot LHV}{\eta_{dg} \cdot \eta_{EM}} = \frac{3.206 \cdot \frac{3.6}{42.2}}{0.385 \cdot 0.985 \cdot 0.995 \cdot 0.985 \cdot 0.97} = 0.800 \text{ kg-}CO_2/\text{kWh at point 2}$$

This adds up to a total GWP at point 2 when sailing in diesel-electric mode of 0.846 kg CO_2-eq/kWh.

Shore power The intrinsic philosophy of the studied concept is to reduce the GWP by sailing in all-electric mode with zero emissions from battery power. Since batteries do not produce greenhouse gas emissions when in operation, this philosophy is correct on a very local level. However, the generation of grid electricity has associated environmental impacts, resulting in an environmental impact at a regional level. This is the GWP of shore power in the WTT phase.

The information from Chapter 6 is used to determine the areas where yachts are most likely to use shore power, and then to determine the regional/national GWP of the grid. The resulting residing areas are those adjacent to the Mediterranean Sea, hence the GWP of the European power grid is used. The European Environment Agency [11] estimated that the current GHG emission intensity of electricity generation in Europe is 0.255 kg CO_2-eq/kWh, decreasing to an estimated average of 0.086 kg CO_2-eq/kWh in 2030.

This indicative value would allow Europe to meet its emissions reduction targets and is therefore a realistic estimate. However, these figures currently include countries with higher carbon intensity than countries adjacent to the Mediterranean Sea , e.g. Poland, which generates most of its electricity from carbon-intensive lignite. A more realistic figure is obtained by averaging the GWP of the electricity grid of neighboring countries only - Spain: 210; France: 56; Italy: 233 g CO_2-eq/kWh - resulting in a GWP of 0.167 kg CO_2-eq/kWh [11]. This figure is significantly lower than the European average, again illustrating the dependence of the results on the available input data.

The TTP phase is considered by looking again at Figure 9.7. It shows that it encounters different efficiencies before it is usable energy at point 2. The GWP of 0.167 kg CO_2-eq/kWh is therefore divided by the associated efficiencies to obtain the total WTP GWP, resulting in 0.181 kg CO_2-eq/kWh at point 2 now. In the future, the grid GWP is expected to decrease to 0.094 kg CO_2-eq/kWh.

$$\text{Current shore power WTP GWP} = \frac{0.167}{0.98 \cdot 0.985 \cdot 0.995 \cdot 0.985 \cdot 0.97} = 0.181 \text{ kg } CO_2\text{-eq/kWh}$$
$$\text{Future shore power WTP GWP} = \frac{0.086}{0.98 \cdot 0.985 \cdot 0.995 \cdot 0.985 \cdot 0.97} = 0.094 \text{ kg } CO_2\text{-eq/kWh}$$

9.3.3. Life cycle assessment

The values determined above are summarised in Table 9.4 and used to perform the LCA. After being used in a yacht, batteries can meet their expected lifetime through second-life application, so this assessment is applied over the lifetime of the battery rather than the lifetime of a yacht. In addition, the expected life of a yacht - approximately ≥ 30 years - does not need to be considered in this way.

Table 9.4: The different sources of emissions and corresponding emission densities involved in the LCA.

Source	**Emissions**	
	Now	Future
	kg CO_2-eq/kWh	kg CO_2-eq/kWh
Battery production CTG	152.6	-
MGO WTP	0.846	-
Shore power WTP	0.181	0.094

The number of compensation cycles determined by Equation 9.13 is the break-even number of charge cycles after which the reduction in operating emissions has compensated for the battery production emissions. As mentioned earlier, this equation is entirely dependent on the correctness of the input data, nevertheless an initial estimate is still made using the values found. Since the input values are all quantified per kWh, the break-even point is independent of battery size.

$$\text{Current compensation cycles} = \frac{152.6}{0.846 - 0.181} = 230 \text{ charge cycles}$$
$$\text{Future compensation cycles} = \frac{152.6}{0.846 - 0.094} = 203 \text{ charge cycles}$$

The manufacturer of the batteries used in this study specified a lifetime of 4000 cycles. If it is assumed that the battery will meet this specified life by given a second life in another industry, then this number of charge cycles can be converted into a lifetime share.

$$\text{Current compensation lifetime share} = \frac{230}{4000} \cdot 100\% = 5.7\%$$
$$\text{Future compensation lifetime share} = \frac{203}{4000} \cdot 100\% = 5.1\%$$

A rough indicative estimate of the maximum annual number of charge cycles for a yacht is made using Equation (9.14)*. Concept version 6, Yacht-M and operational type B, is considered in this calculation. The formula determines the characteristic annual electric nautical miles sailed and divides it by the electric nautical miles per charge cycle. Subsequently, the minimum compensation period can be calculated by dividing the required compensation cycles by this maximum number of annual charging cycles.*

$$\textit{Maximum yearly charge cycles} = \frac{10000 \cdot 0.306}{111} = 27.6 \textit{ Cycles per year} \tag{9.14}$$
$$\textit{Current compensation duration} = \frac{230}{27.6} = 8.5 \textit{ Years} \tag{9.15}$$
$$\textit{Future compensation duration} = \frac{203}{27.6} = 7.5 \textit{ Years} \tag{9.16}$$

These compensation durations are a bare minimum. Therefore, it is expected that the required battery life will significantly exceed ≥ 10 *years. This indicates that the batteries will be on board a yacht for only a portion of their service life. Consequently, only part of the production emissions can be attributed to the application in a yacht.*

When assumed that the specified lifetime is being met, this compensation can be spread over the life of the battery. This ensures that the same share can be used to indicate what share of a charge cycle (instead of life-time) is used to compensate for its production. In addition, this directly indicates what share of a charge cycle the battery is saving emissions - i.e. a battery is currently compensating for its production for 5.7% of a charge-cycle, but 94.3% of a charge-cycle it is saving emissions. In the future, this share is expected to increase to 94.9%.

This emission reduction share of a charge cycle is combined with the theoretical maximum electrical distance share of the different concept versions. These are determined in Section 9.2. This results in an indicative value for the possible impact on sustainability per concept version. These potential impacts are shown in Table 9.5.

$$\text{Environmental impact} = Impact_{distance} \cdot \text{Emission reduction share} \tag{9.17}$$

These values can be achieved if and only if each trip is started with a fully charged battery and the emission parameters correspond to the determined indicative values. These impacts are all significantly higher than the set goal of 10%, although determined with severe boundary conditions.

Besides these two constraints, the impact on the sustainability of a yacht may also change when future alternative energy sources are taken into account with a lower characteristic GWP. This does not lower the environmental impact with use of the intrinsic philosophy of the concept, but lowers the overall emissions of the yacht due to sailing on more sustainable fuels in non-electric modes.

Table 9.5: The impact on sustainability of the different concept version.

Concept version	**Production emissions**	**Emissions saved per cycle**		**Break-even cycles**		**Emission saving share**		**Environmental impact**	
		Now	Future	Now	Future	Now	Future	Now	Future
	[t]	[t]	[t]	[cycles]	[cycles]	[%]	[%]	[%]	[%]
v1-S	265	1.15	1.30	230	203	94.3	94.9	17.6	17.7
v2-S	433	1.89	2.13	230	203	94.3	94.9	24.0	24.2
v3-S	601	2.62	2.96	230	203	94.3	94.9	29.0	29.2
v4-M	678	2.96	3.34	230	203	94.3	94.9	15.0	15.1
v5-M	1292	5.63	6.36	230	203	94.3	94.9	23.0	23.1
v6-M	1905	8.30	9.39	230	203	94.3	94.9	28.8	29.0
v7-L	2922	12.7	14.4	230	203	94.3	94.9	24.5	24.7
v8-L	4503	19.6	22.2	230	203	94.3	94.9	31.3	31.6
v9-L	6084	26.5	30.0	230	203	94.3	94.9	36.4	36.6

9.4. Impact on comfort

A second objective of this study is to sustain or increase the comfort level of a yacht. This symbolises - besides the improved sustainability - the important added value for the owner to consider this concept for his yacht. In Section 2.2 of the concept exploration, it is explained that for the designer it is always a question of the priority that owners give to sustainability over pure luxury. In this section, pure luxury is equated with comfort. Then, when the previously set goal of this study is met, the question of priority disappears and the chance of a possible implementation of the plug-in concept increases significantly.

This concept differs from the diesel-electric benchmark concept only in all-electric operation, so the impact on comfort lies in the difference between the two modes. Comfort aspects such as noise and vibration of installed machinery, smell and image of exhaust fumes, and freedom of operation in ECAs (emission control areas) are considered. An impact on these aspects occurs for the duration of the autonomy, i.e. the AET and AER, and is present respectively during anchoring and sailing, or a combination of both. This occurs when only part of the battery is depleted while at anchor or sailing.

While it is difficult to quantify this impact, some figures are known. While anchored, there is no need for propulsive power, so the AET is the dominant autonomy characteristic. During sailing, the AER is the dominant one. The split in the duration of the two modes is given in Section 2.4 of the concept exploration. There it is stated that yachts are moored or anchored in a bay for 90% of the time. For the remaining only 10% of the time, the yachts are sailing. In Section 9.2, it is stated that during the number of sailings, the time that guests are on board ranges from 60% to 100% for the concept versions. Thus, a noticeable effect in all-electric mode can have a large influence on the yachting experience of on-board guests.

The three different aspects of comfort, where a difference is to be expected, are discussed separately below.

- The first aspect discussed is the effect on the noise and vibration of the installed machinery experienced. The main contributors to this signature on a yacht are considered the HVAC system and the installed propulsion machinery, but hull pressure noise is also present at lower sound frequencies. In order to determine the exact impact of the switch from diesel-electric to all-electric operation, all aspects involved and the corresponding sound paths should be considered. This proved not to be achievable within the given time frame and is recommended as a follow-up study. However, it is still expected that guests will perceive a difference in this signature between the two modes of operation, therefore a qualitative approach is taken.

  Since the generator sets and associated auxiliary machinery on yachts are elastically mounted, their structure-borne sound vibrations are already very low. Their airborne vibrations, or noise, are minimised by covering the engine room walls with insulating materials. Thus, both sources contribute only slightly to the overall sound signature of a diesel-electric yacht, but neither measure can cancel out all noise and vibration from the installed machinery. This results in a potentially noticeable effect. However, S. Matla[1] expects the impact of all-electric sailing compared to diesel-electric sailing to be out of the range of measurement, so there are no numbers to support these expectations. He also expects

[1] An expert at Van Cappellen Consultancy, a company specialising in noise and vibration control for luxury yachts and commercial vessels

the HVAC noise to be dominant during normal operation, with only a minimal noticeable impact in the room directly above the engine room. This noticeable impact increases when the engines are not running according to the normal/trial conditions. All this does not mean that the effect will not be noticed by the guests on board, only that it will be a small effect.

- A more obvious effect is the smell and image of exhaust fumes. Currently, yachts burn fossil fuels to power their diesel generators, emitting polluting gasses and black soot from their exhaust outlets. While sailing, the exhaust outlets just below the waterline are used. As a result, guests hardly notice the exhaust fumes because the yacht has already sailed some distance when they become noticeable. However, when the yacht is at anchor, the exhaust outlets in the mast are used, resulting in a visual of the exhaust fumes above the yacht and possible small amounts of black soot deposits on the canopy. In all-electric mode, the generators are turned off and the yacht runs on batteries, resulting in no exhaust fumes. Whether it is for the duration of the AER when sailing or the AET when anchored, these signatures disappear for a maximum duration of the version-specific autonomy. After that, the generators start, causing the signatures to reappear.
- The last aspect discussed is that of the freedom of operation of a yacht. Section 2.1 explains that the maritime industry is currently subjected to increasingly stringent emission regulations that exclude polluting vessels from certain ECAs. This section also explains that the yachting industry is mainly affected by national regulations, as yachts often fall below the threshold of international regulations. However, these national regulations include the exclusion of polluting vessels in World Heritage Sites and Nature Reserves, the very areas where a yacht would want to stay or tour. When sailing in all-electric mode, this concept has no local emissions and is therefore allowed to sail in these areas. The length it is allowed to reside or tour in these areas is limited to the concept-specific autonomy. It is expected that the number of these areas will increase in the future, which will increase the benefit of this concept by itself.

From this qualitative analysis, it can be concluded that the comfort levels increase only slightly, but are certainly sustained. Although this conclusion naturally depends entirely on the aspects considered, the most important ones have been mentioned in this section. The objective set for this study has therefore been achieved.

9.5. Impact on operation

The third and final objective of this study is to maintain the operational performance of a diesel-electric yacht for the plug-in concept. In the design process of the concept, the size of the installed generator sets is reduced to a required size to power only cruising speeds. Therefore, an inherent impact on operational capability is expected. To partially compensate for this effect, the available power of the installed battery modules is used. However, the battery modules are limited in power output and have low energy storage capacity. The limited available power affects the speed window that a yacht can sail in all-electric mode. In order to maintain the same speed window in the plug-in concept, the available power of the different operating modes is studied. The limited stored electrical energy affects the endurance of the concept at different speeds and modes of operation. This is visualised in an operating profile envelope, which is therefore determined.

9.5.1. Operating modes

The benchmark configuration powers the entire speed window in Diesel-Electric (DE) mode. In the design process, the generator sets are decreased in size so that they are only able to power the cruising speeds.

$$P_{DE} = P_{gens} = P_{cruise} \tag{9.18}$$

The studied concept is able to power the yacht using battery power only. However, a battery module is limited in its power output due to its characteristic C-rate. Section 2.5 explains that this is a dimensionless power factor. Multiplying this characteristic by the installed battery capacity results in the available power in All-Electric (AE) mode.

$$P_{AE} = P_{batt} = E_{batt} \cdot C_{rate} \tag{9.19}$$

This limit on available battery power limits the all-electric speeds of the yacht. However, when the batteries are combined with the (smaller) generator sets in Hybrid (H) mode, the two available power sources are combined in a higher total available power. This results in a wider speed range the yacht is able to sail.

$$P_H = P_{batt} + P_{gens} \tag{9.20}$$

9.5.2. Operating envelope

The impact on operational capability can be visualised in a possible operational profile envelope depicted in the trip scatter of the available dataset. This shows the distance the yacht can sail over the speed spectrum. This is calculated using Equation (9.21). To determine this envelope per concept version, the maximum operating time within its speed spectrum is calculated as a function of the available energy and power. A distinction is made between the all-electric, diesel-electric and hybrid modes of operation mentioned above.

$$\begin{aligned} d &= v_s \cdot t \\ &= v_s \cdot \frac{E}{P} \end{aligned} \tag{9.21}$$

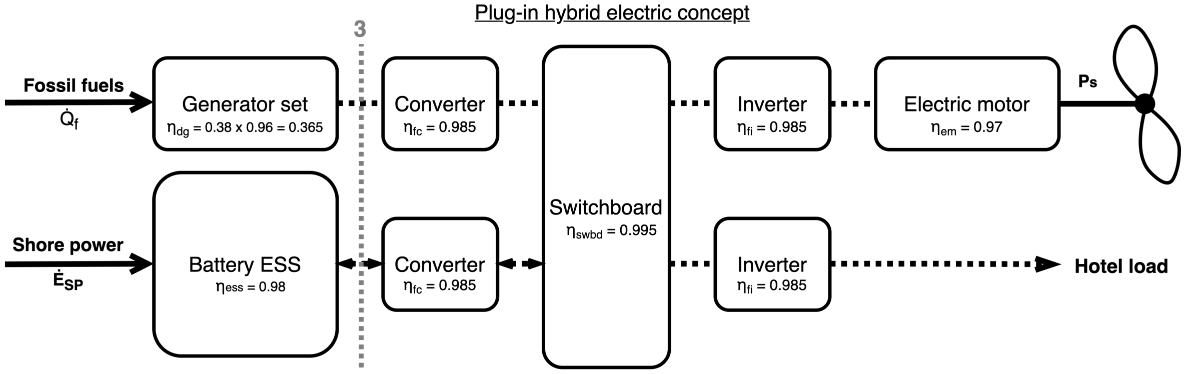


Figure 9.8: The configuration of the concept and the efficiencies of its corresponding components, with point 3 denoted.

First, the total energy capacity stored on board is determined, which is in MGO or in battery modules. The MGO energy capacity (E_{MGO}) per yacht is determined using the tank volume (V_{tank}), fuel density (ρ_{MGO}) and lower heating value (LHV_{MGO}) of MGO. The density and lower heating value are $0.86 kg/L$ and $42.7 MJ/kg$, respectively [59]. The installed energy capacity of the battery (E_{batt}) depends on the concept version.

$$E_{MGO,3} = V_{tank} \cdot \rho_{MGO} \cdot LHV_{MGO} \cdot \eta_{dg} \tag{9.22}$$

$$E_{batt,3} = E_{batt} \tag{9.23}$$

Similar to the method discussed in chapter 7, the sum of the two energies stored on board is not equal to the total usable energy for the two consumers - i.e. hotel and propulsion power. In Figure 9.8 it is shown that both energies encounter different efficiencies, hence point 3 is chosen as the point of comparison. See section 7.6 for the resulting efficiencies - electrical-mechanical efficiency (η_{EM}) is 93.6% and electrical-electrical efficiency (η_{EE}) is 96.5%. The battery efficiency shown is the efficiency when charging with shore power, due to heat dissipation. This is not applicable in this calculation as it is defined that the battery is fully charged at the start of the trip. The resulting available energies are shown in Table 9.6.

The second thing to be determined is the consumers of this energy. These are the constant hotel power (P_{hotel}) and the required propulsion power (P_{prop}). The adjusted speed-power curves per concept version are used to determine this power. Recall that the supplied curves indicate shaft power (P_s), so the electrical-mechanical losses up to point 3 must be included in this calculation.

$$P_{prop,3} = \frac{P_s}{\eta_{EM}} \tag{9.24}$$

$$P_{hotel,3} = \frac{P_{hotel}}{\eta_{EE}} \tag{9.25}$$

$$P_{tot,3} = P_{prop,3} + P_{hotel,3} \tag{9.26}$$

Table 9.6: The available energies of both energy sources at point 3.

Concept version	**Tank volume**	**Energy available (point 3)**	
		MGO	Battery
	[m^3]	[MWh]	[MWh]
v1-S	30.2	120.2	1.7
v2-S	30.2	120.2	2.8
v3-S	30.2	120.2	3.9
v4-M	132	525.8	4.4
v5-M	132	525.8	8.4
v6-M	132	525.8	12.4
v7-L	419	1669	18.9
v8-L	419	1669	29.2
v9-L	419	1669	39.6

Third, the maximum operating time of the different modes is calculated. Similarly Similar to the powers, the names of the different operating modes denote the energy sources. This ensures that different amounts of energy are available for the different operating modes. Combined with the power requirements of the same mode, this results in different maximum operating durations for the different modes.

$$t_{AE} = \frac{E_{batt,3}}{P_{tot,3}} \tag{9.27}$$

$$t_{DE} = \frac{E_{MGO,3}}{P_{tot,3}} \tag{9.28}$$

$$t_H = \frac{E_{batt,3} + E_{MGO,3}}{P_{tot,3}} \tag{9.29}$$

At last, multiply this duration by the yacht specific speed window according to Equation (9.21). This gives the maximum distance the concept can sail in a specific mode. To give an indication of the impact on the operational profile, the benchmark configuration is also calculated. All resulting operation envelopes are shown in Appendix E.

These figures show that a significant portion of the original operating profile can be sailed with the new configuration. Only trips sailed at high speed over a long distance are excluded in this concept. It is questionable to what extent the guest experience is affected by this exclusion, but no data on actual guest trips is known to confirm this. The figures continue to show that the range constantly increases per concept version, even though the power demand is also increasing due to the increased draught. Ultimately, the range in all-electric mode, as designed, is substantial. Only in concept version 1 does a power limit of the batteries occur, see Figure 9.9. As the installed battery capacities increase, this limit disappears.

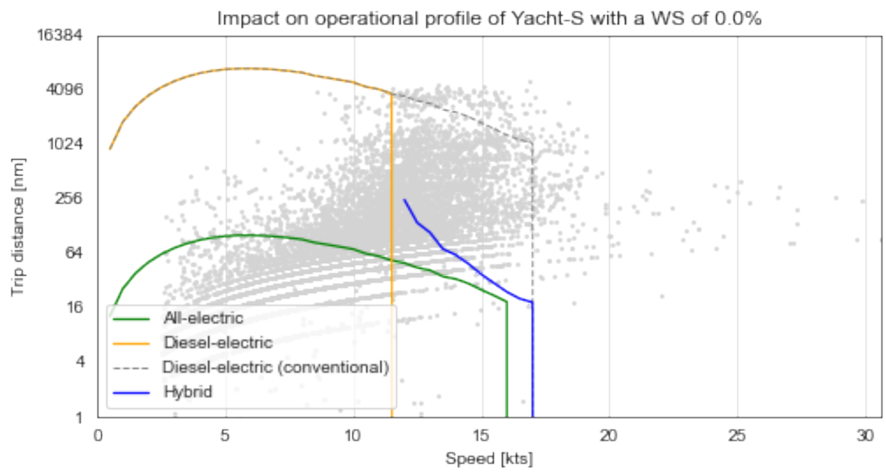


Figure 9.9: The impact on the operational profile of concept version 1, Yacht-S with a weight-share addition of 0.0%.

10

Test itinerary

In order to gain more insight into the actual utilisation of the various installed battery capacities in combination with the available shore power, a test route was sailed. Detailed usage statistics did not reveal a specific itinerary, so a proposed usage scenario needs to be developed based on the predicted usage of the concept. As the plug-in hybrid electric concept is new and involves increased use of charging infrastructure, previous superyacht usage data is used only as a guide.

Most cruises are 7-14 days in duration, with the vast majority occurring during the long and warm summer months. During these months, most yachts are located in the Mediterranean Sea. During this time, dawn in the Mediterranean rises around 6:00am and sets around 9:00pm. This results in long days (≈ 15hrs) being available for sailing and other activities. These activities may consist of swimming and use of on-board toys, a sunset dinner, and/or sightseeing in a nearby town or scenic spot. In addition, the ultra-rich have their own hotspots in this area where they can meet up with their peers.

Based on these usage characteristics, this itinerary is sailed in the Mediterranean Sea, along the French and Italian coasts. It has a guest duration of one week, after which the captain sails to his main port in one day. The cities and anchorages visited are: Monaco, Calvi, Malfacu Bay, Saint-Florent, Bastia, Porto Santo Stefano, Capri and Naples. The intended use is implemented in the itinerary shown in Figure 10.1. Possible restrictions on access to ports during the itinerary are not considered. A brief description of the test itinerary is defined in Table 10.1, a detailed version is provided in the appendix, TableF.1.

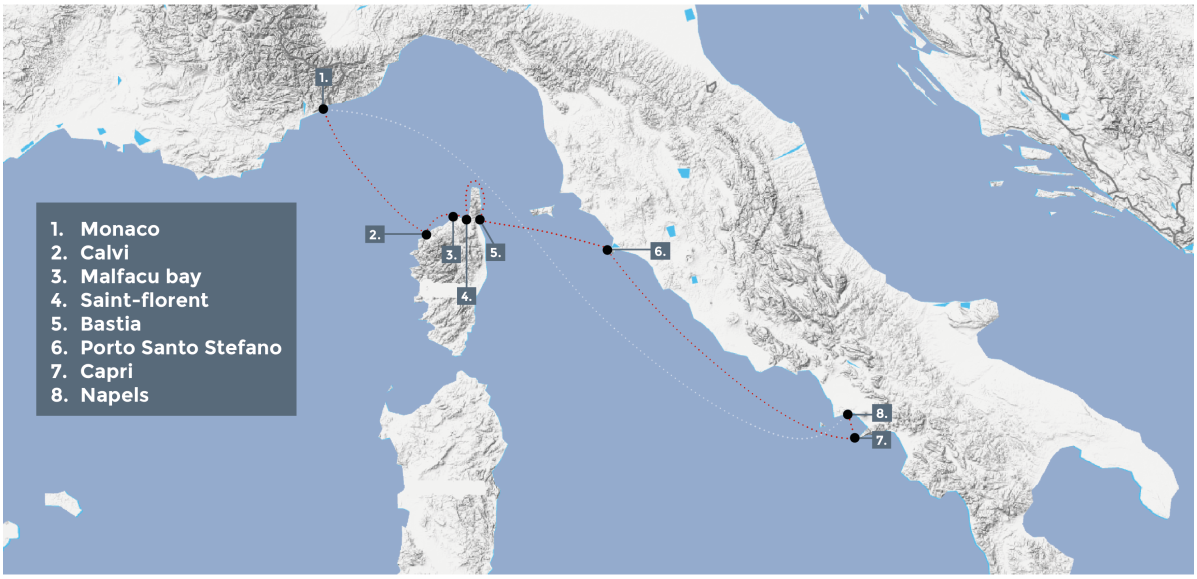


Figure 10.1: A visualisation of the test itinerary along the France and Italian coast.

Table 10.1: A brief description of the test cruise in the Mediterranean.

Day	Departure	Destination	Charge	Day	Departure	Destination	Charge
1	Monaco	Calvi	Yes	5	Bastia	Porto Santo Stefano	Yes
2	Calvi	Malfacu Bay	No	6	Porto Santo Stefano	Capri	Yes
3	Malfacu Bay	Saint-Florent	Yes	7	Capri	Capri (via Napels)	Yes (No)
4	Saint-Florent	Bastia	Yes	8	Capri	Monaco (via Napels)	Yes (No)

In the operating modes run on during this test cruise, a distinction is made between cruise, transit, anchorage, or berthed in port. The difference between anchorage and port is the charge availability. The difference between the other two modes is the time of day and the speed sailed - cruise is sailed at all speeds during the day and transit is sailed at lower (quieter) speeds at night. Sometimes a captain will leave the marina early in transit mode in order to arrive at the destination port on time. The speeds during these trips are mostly dependent on the arrival time and are shown in the operating profile in Figure 10.2.

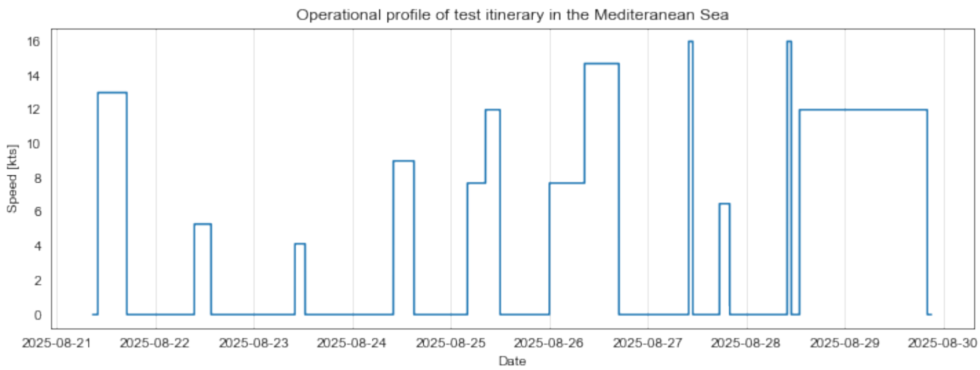


Figure 10.2: The operational profile of the test itinerary.

This test cruise is sailed with all three yachts. In this chapter, only the results of Yacht-M are shown, as the shore power scenarios have a significant impact; however, all results are given in Appendix F. The previously determined operating profile is used to determine the energy consumption over the course of the trip in combination with the adjusted speed-power curve. For simplicity, only the speed-power curve of the version with a 2.5% WS-addition was used. Due to the rather small difference ($\leq$ 1.65%) in power required at maximum speed between this version and the 0.0% and 5.0% versions, this is considered valid. Combining the operating profile with the corresponding power curve results in the power demands shown in Figure 10.3. The resulting energy consumption of the yacht during the cruise is shown in Figure 10.4.

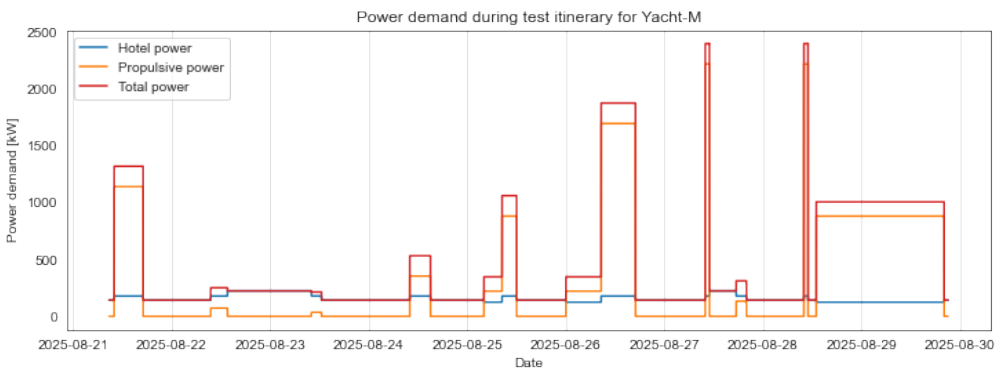


Figure 10.3: The power demand of Yacht-M over the course of the test itinerary.

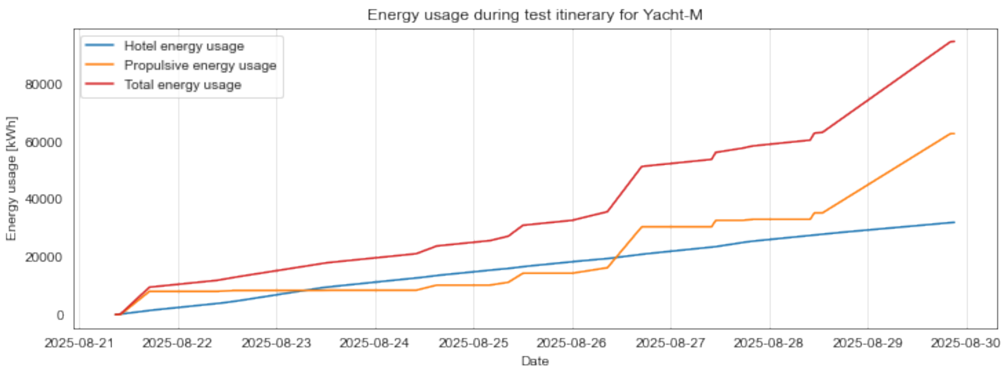


Figure 10.4: The energy consumption of Yacht-M over the course of the test itinerary.

During this itinerary, the yacht visits several marinas where the concept can recharge, as shown in Table 10.1. Thorough research on available shore power at these exact locations did not yield the desired results, so the calculated area average available shore power of Chapter 6 is used. Note that within this figure there may be a large discrepancy between the value used and the actual value. Within this test route, the same three different scenarios are reviewed: current available infrastructure, predicted future available infrastructure, and desired future available infrastructure. This results in the following available shore powers:

- The current infrastructure has an average available shore power of $594kW$.
- The current infrastructure is expected to increase to an average available shore power connection of $850kW$ in the future.
- There are marinas present that have a much more powerful shore power connection available. If the owner visits these marinas more frequently and the average available shore power connection increases, a desired future shore power connection of $1250kW$ is estimated to be available.

Section 2.5 explains that the State-of-Charge (SoC) expresses the ratio of the remaining available energy capacity of the battery. This SoC is directly related to the energy consumption during the test route or, if moored in a marina, directly related to the available shore power. Within the above mentioned three available shore power scenarios, the SoC of the installed batteries behaves differently. For example, a shore power connection of $1250kW$ will charge much faster than the connection of $594kW$ in the same time period. However, as explained in Chapter 6, the hotel power has to be taken into account first, resulting in a lower available charging power. The resulting SoC diagrams in the different scenarios for Yacht-M during the cruise are shown in Figures10.5 to 10.7. The moment the battery is depleted (SoC is 0.00%), the generators are needed to power the yacht. When the battery is fully charged (SoC is 100%), shore power is used only to power the hotel loads.

The first figure shows that the battery capacities are hardly fully utilised, resulting in the generators being needed to power the yacht multiple times. The time in port for the two larger batteries (WS 2.5% & 5.0%) is too small to charge them significantly, which is due to the rather poor availability of shore power.

The remaining two scenarios show a more convincing utilisation of the installed batteries for this yacht. They show that increasing the available shore power results in faster charge cycles, allowing batteries with a larger capacity to become fully charged. In addition, the effect of a smaller battery size is more visible - i.e. the smallest battery (WS 0.0%) is quickly depleted, but also quickly recharged when in port. This results in the generators being switched on more frequently and for longer periods of time to provide power to the yacht than the larger batteries. Designers are therefore able to implement this concept in future designs of medium sized vessels.

The figures in Appendix F show the negative effect of implementing the concept in a large yacht. They show that the charging times of these much larger batteries are unacceptably long, as less charging power is available due to the larger hotel power demand. Accordingly, it is expected that this concept is unlikely to be implemented in large yachts.

In contrast, the concept versions of the small yacht have rather short charging times, which currently already fit into a regular port stay. These concept versions are capable of providing battery power to the yacht for a significant period of time and range. Therefore, a designer can already design a small superyacht installed with this concept that uses its batteries for a significant portion of its annual operating profile.

Finally, it should be noted that these results show the high dependence of the concept on the available shore power supply and the actual use of the yacht. If a guest does not want to enter a marina, does not visit marinas with sufficient shore power supply, or visits a marina for too short a time, the battery utilisation drops.

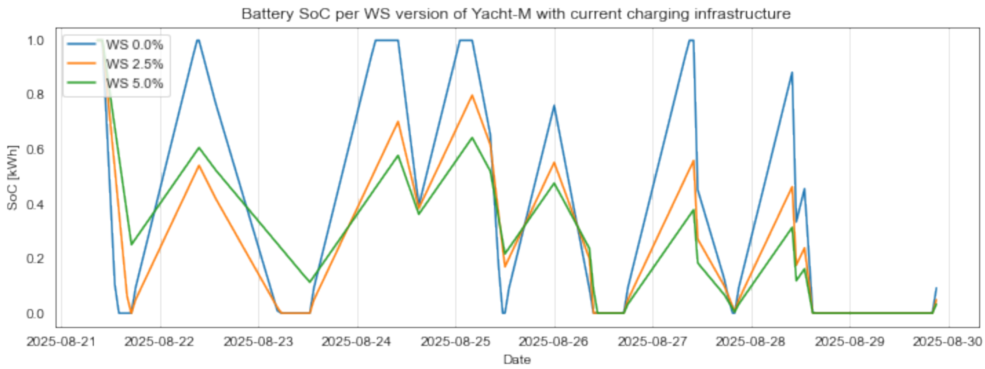


Figure 10.5: The State-of-Charge of the installed battery per concept version of Yacht-M during the test cruise in the current shore power scenario ($594 kW$).

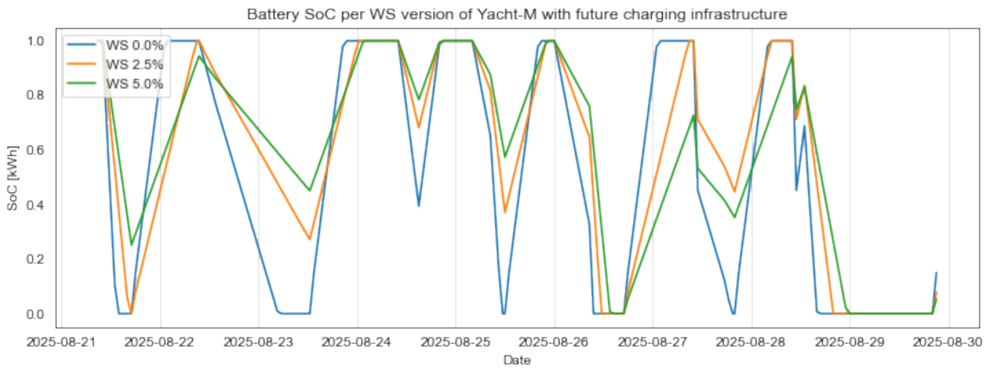


Figure 10.6: The State-of-Charge of the installed battery per concept version of Yacht-M during the test cruise in the future shore power scenario ($850 kW$).

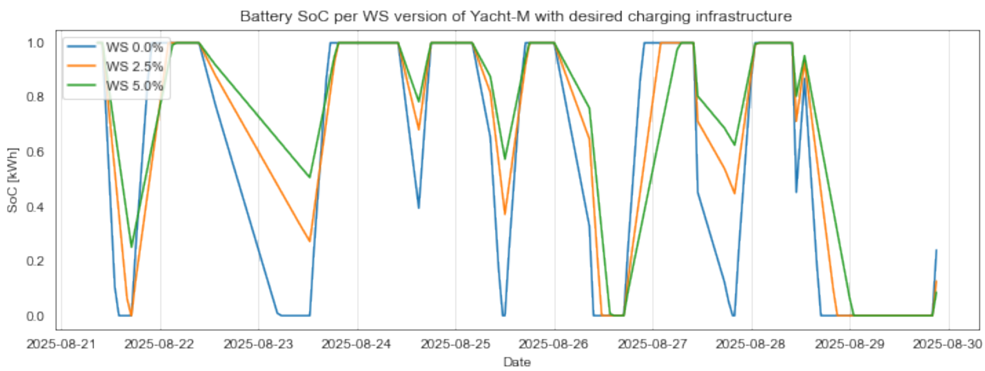


Figure 10.7: The State-of-Charge of the installed battery per concept version of Yacht-M during the test cruise in the desired shore power scenario ($1250 kW$).

11 Conclusion

The introduction addressed why Feadship is interested in the plug-in concept, accompanied by the main research question and sub-questions. The objective of this research was to provide a proof of concept of a plug-in hybrid electric superyacht, based on three predefined goals. These goals were to increase sustainability by 10%, sustain or increase comfort levels, maintain operational capability. In this report, nine different parametric concept designs are presented in this report. The design philosophy for these concept versions is to sail part of the fossil fuel distance on shore power, while simultaneously minimising the impact on yacht design. This way, Feadship could expand its propulsion system portfolio with a more sustainable concept that is feasible in the near-future, and which is interesting for the client. An answer to the main research question is provided by discussing the answers to the sub-research questions. Based on this, the final conclusion on the research objective is drawn.

11.1. Conclusion on research questions

The five sub-research questions are discussed separately.

What is the expected operational usage of a plug-in hybrid electric superyacht?

To obtain insight into the expected operational usage of the concept, a statistical analysis was performed based on operational voyage data of the Feadship fleet. It is promising that a scatter of the data shows that trips of a smaller distance are mostly sailed on lower speeds and longer distance trips on higher cruising speeds. Guest presence results in a large speed variance at medium trip distances. Although different operational aspects are not taken into account, this mild correlation still underlines the opportunity of this concept to sail those shorter distances with a lower energy demand on shore power.

Statistics are used to obtain design values for the concept. It resulted in a single design speed that is equal to the cruising speeds of a yacht. A Froude number versus waterline length relation yields the exact cruising speeds for the three different sized benchmark yachts. Statistics furthermore showed that the concept should not be designed for a single all-electric autonomy, but a range between $25nm$ and $200nm$. These results were used to determine the required battery capacity of the concept versions.

What are the basic design parameters of required equipment on the market?

Batteries are characterised by their low specific gravimetric energy density. The allowable additional weight due to batteries is limited within the concept versions. Therefore, an analysis of the available market solutions was performed to obtain the battery parameters of the type with the best gravimetric energy density. The result was the liquid cooled Akasol 9AKM 150 CYC. Due to the liquid cooling, a heat exchanger and additional piping are required as auxiliary equipment, as well as a service space for maintenance.

In order to minimise the impact on design, the installed generators are decreased in size. Therefore, a regression analysis was performed that resulted in power dependent design parameters. The additional required auxiliary equipment was a DC-DC converter, a DC switchboard part to control the battery modules, and service spaces for maintenance.

What is the available current and future shore power infrastructure?

The available shore power is determined by a questionnaire that was distributed worldwide. The survey linked the marina location to the current shore power available. This information was finally used to give an indication of the shore power available in typical superyacht areas. The data itself showed a large variation between obtained values and may therefore only be used as an indication. The resulting indications are presented in Table 6.1 and shows that the Mediterranean has the best available shore power supply.

This shore power is not directly available as charging power for the batteries. For this, the required hotel power of a yacht has to be subtracted from the shore power. This depends on the size of the yacht (GT), therefore the available charging power varies considerably between the different concept designs, resulting in only a small charging power remaining for the large yacht. In the Mediterranean, this currently results in an average charging power of slightly less than $200 kW$ for a large yacht. Table 6.2 shows the available charging powers in the different regions for all three yacht sizes, showing good and moderate charging powers for respectively the small and medium sized yachts.

The survey results give an indication of the shore power available in the future. The marinas expect an increase in demand of shore power for yachts and therefore also expect an increase in supply. To take this into account, three different scenarios are considered: current; future; desired. The resulting charging powers are shown in Table 6.4. In all scenarios, the shore power supply approximately doubles. These scenarios show that the available charging powers, i.e. the feasibility of the envisioned concept, increases significantly over time as the available shore power supply increases. However, the Caribbean is excluded for this concept as the available charging power is too low.

What are the resulting parametric designs of the concept?

The resulting parametric designs and characteristics of the concept versions are shown in Table 8.10.

What are the characteristic effects of the concept on design, sustainability, comfort, and operation?

The impact on yacht design is minimised in the design process by compensating the added weight of the configuration and compensating the absorbed volume by decreasing the size of the generators. The resulting impacts are shown in Table 9.2. The added weight-shares range from 0.0% and 5.0%. The approximation of the additional absorbed volume-shares ranges from −0.2% to 1.2%. This is within the early stage design margins of a yacht and therefore is the objective of minimising impact on yacht design achieved.

A life-cycle assessment is performed to quantify the impact on sustainability. The impact on sustainability is shown in Table 9.5. It shows that currently the impact ranges between 15.0% and a maximum theoretical value of 36.4% among the concept versions. In the future, this increases to 15.1% and a maximum theoretical value of 36.6% among the concept versions. These seriously high emission savings can only be achieved if and only if each trip is started with a fully charged battery and the emission parameters correspond to the determined indicative values. The resulting impacts are all higher than the set goal of 10%, although determined with the severe constraint that the shore power infrastructure must be sufficient.

The added value for the owner mostly comprises of the extra comfort he can experience when sailing all-electric. The all-electric autonomy the owner will experience ranges from 65% to all of the trips. Three aspects are considered during these trips: Noise & vibration; Smell & image exhaust gasses; Freedom of operation. The effect on noise and vibration of the installed machinery is expected to be non-measurable but noticeable when on board. During all-electric operations, exhaust gasses are absent, resulting in no foul odour of burning fuels and no visual out of the exhaust outlets. Furthermore, during the operations powered by batteries, yachts are allowed in more areas. Especially in the very areas where a yacht resides: World Heritage Sights and Nature Reserves. These additional allowed areas are expected to increase in the coming years. The objective is therefore achieved, since it can be concluded that the comfort levels increase only slightly, but are certainly sustained.

By using battery power to compensate for the decrease in installed generator power, the impact on operation is minimised but not zero. Only trips sailed at high speed over a long distance are excluded in this concept. It is questionable to what extent the guest experience is affected by this exclusion, but no data on actual guest trips is known.

11.2. Conclusion on research objective

The objective of this research was:

Provide a proof of concept of the plug-in hybrid electric superyacht and describe its effects.

Based on the designs produced, the test cruise sailed, and the answers to the research questions, it can be concluded that a proof of concept is provided for a small and medium sized yacht. For large yachts, this concept is not expected to be implemented due to the unacceptably long charging times. For almost all designs, the design and operational impacts are minimised, while the sustainability and comfort impacts meet or exceed the set targets. The major constraint for this concept is the available shore power infrastructure. Although, as the superyacht market shifts towards the operation of many plug-in hybrid superyachts, the available shore power supply at marinas is expected to increase at the same time.

The concept can already be implemented in a small yacht operating in the Mediterranean or Adriatic. The impact on yacht design of the concept version with the largest battery module installed is limited to a maximum value of 0.6% of additional absorbed volume and 5.0% of additional weight. This includes the smaller generators, the battery modules, and the auxiliary equipment. This concept version can power the hotel operations for about $60hr$, cruise $9.5hr$ in battery mode or sail $112nm$ at cruise speed. Annually, this results in a theoretical maximum environmental impact of 29.0%, which may increase to as much as 29.2% in the future when sustainability of the power grid increases.

The concept can be implemented in a mid-sized yacht operating in the Mediterranean or Adriatic Sea if shore power infrastructure has improved in the future. The impact on yacht design of the concept version with the largest battery module installed is limited to a maximum value of 1.1% of additional absorbed volume and 5.0% of additional weight. This includes the smaller generators, the battery modules, and the auxiliary equipment. This concept version can power the hotel operations for about $70hr$, cruise for $8.2hr$ on batteries or sail for $111nm$ at cruising speed. Annually, this results in a theoretical maximum environmental impact of 28.8%, which may increase to 29.0% in the future when sustainability of the power grid increases.

These figures are ambitious and are considered indicative values only. They are entirely dependent on input values and set conditions. For example, it is highly unlikely that the yacht will be able to fully charge its batteries before each trip. Accordingly, the stated emission reduction values will be lower.

Nevertheless, the potential that a hybrid propulsion system has is serious! Analysis of operational voyage data has shown that the characteristic operational profile of a yacht consists predominantly of short-distance trips at low to medium speeds. With only 2% to 3% of the full range capability, ≥ 70% of the trips can be sailed. The continuous effect on nautical miles sailed results in an impact on the annual distance sailed of ≥ 30%. This highlights the opportunity for the yachting industry to explore any sustainable hybrid solution in the future.

12

Discussion & Recommendations

When research is carried out, assumptions and simplifications on various topics are inevitable. To what extend these cause for errors or influence the final result is discussed in Section 12.1. The recommendations for further research are discussed in Section 12.2.

12.1. Discussion

Discussing all assumptions and simplifications would result in an overkill. Therefore, only the most important topics are discussed.

- The voyage data analysis carried out, used AIS data where no distinction was made in type of arrival or departure location. Therefore, it was assumed that every trip is a port-to-port trip. It follows that the concept would be able to start each trip with a fully charged battery. This may lead to an optimistic estimate of nautical miles sailed purely on electricity, however the use of a superyacht is entirely subject to the wishes of the guests. They determine the actual usage and port calls of the yacht. If guests constantly want to visit marinas with good shore power supply, then this assumption is a reality. Therefore, this assumption is valid.
- In addition to the above, the wide variation in shore power availability results in a possibility of over- or underestimating the actual shore power available. But again, this is entirely dependent on the actual usage and port calls of the yacht. This report shows the potential of the concept with estimated averages. If the actual figures are lower or higher, this is reflected in the calculated potential.
- The regression analyses performed are used to provide a rough indication of the size and weight of the equipment needed. The dataset used for both energy and power auxiliary equipment is limited in size. Therefore, although the contribution of auxiliary equipment to the total is not large, more data could improve the result. The validity of a linear regression for specific equipment can be questioned. Further use of the resulting regression parameters assumes that the space can be completely filled. In reality, this is always likely to be less. This therefore means that the values shown are only indicative and the final values will always be design-specific.
- The theoretical maximum values of the impact on sustainability that have been determined seem optimistic, and they are. They can only be achieved if the battery reaches its expected lifetime, the concept reaches its theoretical maximum impact on nautical miles sailed per year, and the determined emission values are similar to the actual values. In particular, a large discrepancy between the determined and the actual values is to be expected for the emission values. This is mainly due to the large number of aspects that have to be taken into account.
- All calculations assume that the machinery has constant efficiencies during all operating conditions. In reality, this is not the case. Batteries have constant efficiencies throughout operation, but in contrast, generator sets achieve their efficiencies only at a nominal rating. This leads to a discrepancy between actual and real values at part load conditions. However, the core of this study focuses on battery usage and associated impacts, calculated at cruising speed. Therefore, the effect is expected to be minimal.

12.2. Recommendations

Based on the discussion, several recommendations for future studies are presented. Besides refining of some parameter estimations, it is advised to study the extent of some impacts more in-depth.

- The impact on design is based on the results of regression analyses. Therefore, the search for theoretical correlations rather than empirical correlations, if any available, should lead to improved design parameters. These improved design parameters will lead to improved estimates and a better informed designer of the concept.
- The impact on comfort is determined by a qualitative analysis of comfort levels. In addition, an expert is asked about his expectations. Combining these, one arrives at uncertain expectations, while these estimates are an important decision factor for the client. Therefore, quantifying these estimates would greatly improve the basis of this new concept. The impact on noise and vibration levels can be quantified by examining all sound paths emanating from the engine room within the yacht.
- The impact on sustainability is entirely dependent on the input values of the calculation. Since this impact is an important decision factor for considering this concept, a more detailed and accurate LCA for batteries used in yachts would lead to a more solid justification. Within this assessment, a more accurate impact of battery production location should be included, combined with an accurate impact of second life and recycling emissions.
- Not all advantages of the plug-in hybrid electric concept are studied in this research. Especially, the effect of different operating modes is not studied. For example, the effect of simultaneously charging the batteries and powering the yacht on emissions and operational capability is not studied. While this could significantly increase the cruising experience of on board guests.
- At last, this study has proven the potential of any sustainable hybrid propulsion system. Therefore, it is strongly advised to examine other sustainable hybrid concepts that have a durability of only a small part of the full range capability.

Bibliography

[1] A.K. Ådnanes. Maritime electrical installations and diesel electric propulsion. Technical report, 2003.

[2] AKASOL - Battery Systems. 9 AKM 150 CYC. Technical report. URL www.akasol.com.

[3] R. Akershoek. Design of a fully electric super yacht. Master's thesis, Delft University of Technology, 2018.

[4] A.F. Burke and C.B. Somuah. Power train trade-offs for electric and hybrid vehicles. *Digest of Papers - FTCS (Fault-Tolerant Computing Symposium)*, 1980. doi: 10.1109/vtc.1980.1622814.

[5] J. Carlton. *Marine propellers and propulsion.* Butterworth-Heinemann, 2018.

[6] M. Chen, X. Ma, B. Chen, R. Arsenault, P. Karlson, N. Simon, and Y. Wang. Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries, 11 2019. ISSN 25424351.

[7] De Voogt Naval Architects. User profile of a yacht. Internal document, n.d.

[8] DNV-GL. Maritime forecast to 2050. *Energy transition outlook*, 2018, 2018.

[9] DNV-GL. Norway challenges the cruise industry to operate emission free, 2019. URL https://www.dnvgl.com/expert-story/maritime-impact/Norway-challenges-the-cruise-industry-to-operate-emission-free.html.

[10] L.A. Ellingsen, G. Majeau-Bettez, B. Singh, A.K. Srivastava, L.O. Valøen, and A.H. Strømman. Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. 2013. doi: 10.1111/jiec.12072. URL www.wileyonlinelibrary.com/journal/jie.

[11] European Environment Agency. Greenhouse gas emission intensity of electricity generation, 2021. URL https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-8#tab-googlechartid_googlechartid_googlechartid_googlechartid_chart_11111.

[12] J. Faber, S. Hanayama, S. Zhang, P. Pereda, B. Comer, E. Hauerhof, and H. Yuan. Fourth IMO GHG Study. Technical report, International Maritime Organisation (IMO), Delft (NL), 2020.

[13] Feadship. Aeon, 2009. URL https://www.feadship.nl/designs/project-aeon.

[14] Feadship. Breathe, 2010. URL https://www.feadship.nl/designs/project-breathe.

[15] Feadship. Savannah, 2015. URL https://www.feadship.nl/fleet/savannah.

[16] Feadship. Lonian, 2018. URL https://www.feadship.nl/fleet/lonian.

[17] Feadship. Escape, 2020. URL https://www.feadship.nl/designs/escape.

[18] R.D. Geertsma, R.R. Negenborn, K. Visser, and J.J. Hopman. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Applied Energy*, 194:30–54, 2017. ISSN 03062619. doi: 10.1016/j.apenergy.2017.02.060.

[19] Greenline Yachts. Propulsion - From traditional to full electric. URL https://www.greenlinehybrid.com/en/propulsion.

[20] N. Hall, D..and Lutsey. Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions. 2018.

[21] J.F. Hansen and F. Wendt. History and State of the Art in Commercial Electric Ship Propulsion, Integrated Power Systems, and Future Trends. In *Proceedings of the IEEE*, volume 103, pages 2229–2242. Institute of Electrical and Electronics Engineers Inc., 12 2015. doi: 10.1109/JPROC.2015.2458990.

[22] G. Harper, R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, Al. Walton, P. Christensen, O. Heidrich, S. Lambert, A. Abbott, K. Ryder, L. Gaines, and P. Anderson. Recycling lithium-ion batteries from electric vehicles. *Nature*, 575:75, 2019. doi: 10.1038/s41586-019-1682-5. URL `https://doi.org/10.1038/s41586-019-1682-5`.

[23] B. Huang, Z. Pan, X. Su, and L. An. Recycling of lithium-ion batteries: Recent advances and perspectives, 9 2018. ISSN 03787753.

[24] S. Hwang, B. Jeong, K. Jung, M. Kim, and P. Zhou. Life Cycle Assessment of LNG Fueled Vessel in Domestic Services. *Journal of Marine Science and Engineering*, 7(10):359, 10 2019. ISSN 2077-1312. doi: 10.3390/jmse7100359.

[25] IEA. CO2 Emissions from Fuel Combustion: Overview – Analysis, 2020. URL `https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview`.

[26] IEA. Renewables 2020 – Analysis and forecast 2025, 2020. URL `https://www.iea.org/reports/renewables-2020/renewable-electricity-2#abstract`.

[27] IMO. International convention on tonnage measurement of ships, 1969.

[28] IMO. MEPC.1/Circ.684 - GUIDELINES FOR VOLUNTARY USE OF THE SHIP ENERGY EFFICIENCY OPERATIONAL INDICATOR (EEOI). Technical report, 8 2009.

[29] IMO. MEPC.1/Circ.723, 2010.

[30] IMO. Resolution MEPC.190(60), 2010.

[31] IMO. Resolution MEPC.286(71), 2017.

[32] IMO. Reducing greenhouse gas emissions from ships, 2020. URL `https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx`.

[33] H. C. Kim, T. J. Wallington, R. Arsenault, C. Bae, S. Ahn, and J. Lee. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis. 2016. doi: 10.1021/acs.est.6b00830. URL `https://pubs.acs.org/sharingguidelines`.

[34] H.J. Klein Woud and D. Stapersma. Design of Propulsion and Electric Power Generations Systems. *Published by IMarEST, The Institute of Marine Engineering, Science and Technology. ISBN: 1-902536-47-9*, 2002.

[35] J. Kumar, L. Kumpulainen, and K. Kauhaniemi. Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions. *International Journal of Electrical Power and Energy Systems*, 104:840–852, 1 2019. ISSN 01420615. doi: 10.1016/j.ijepes.2018.07.051.

[36] LLoyd's Register. Rules and Regulations for the Classification of Special Service Craft. Technical Report July, 2020. URL `http://www.lr.org`.

[37] R. Marella-Daw. The Sustainable Future of Superyachts | Yachts & Jets | Drive. *Luxury London*, 6 2019. URL `https://luxurylondon.co.uk/drive/yachts-and-jets/sustainable-superyachts`.

[38] C. McKerracher, A. Izadi-Najafabadi, A. D'Donovan, N. Albanese, N. Soulopoulos, D. Doherty, M. Boers, R. Fisher, C. Cantor, J. Fith, S. Mi, and A. Grant. Electric Vehicle Outlook 2020. Technical report, Bloomberg N.E.F., 2020.

[39] Monaco Yacht Show. Trends in superyachting, 2019. URL `https://www.monacoyachtshow.com/en/press/mystories/mystories-detail/989-trends-in-superyachting.html`.

[40] V. Moreno Sáiz and A. Pigazo López. Future Trends in Electric Propulsion Systems for Commercial Vessels. *Journal of Maritime Research*, 4(2):81–100, 2007. ISSN 1697-9133.

[41] R.J. Nessink. Consultancy study - High-powered yacht propulsion systems. Technical report, De Voogt Naval Architects, 2014.

[42] J Neubauer, K Smith, E Wood, and A Pesaran. Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries. Technical report, 2015. URL www.nrel.gov/publications.

[43] J.G. Nijhoff. Multibody Superyachts. Master's thesis, Delft University of Technology, 2017.

[44] K.L. Odendaal. Enhancing early-stage energy consumption predictions using dynamic operational voyage data - A grey-box modelling investigation. Master's thesis, Delft University of Technology, The Netherlands, 2021.

[45] J. F. Peters, M. Baumann, B. Zimmermann, J. Braun, and M. Weil. The environmental impact of Li-Ion batteries and the role of key parameters – A review, 1 2017. ISSN 18790690.

[46] P. Plötz, S.A. Funke, P. Jochem, and M. Wietschel. CO2 Mitigation Potential of Plug-in Hybrid Electric Vehicles larger than expected. *Scientific Reports*, 7(1), 12 2017. ISSN 20452322. doi: 10.1038/s41598-017-16684-9.

[47] Polestar. Life cycle assessment | Carbon footprint of Polestar 2. Technical report, 2020. URL https://www.polestar.com/dato-assets/11286/1600176185-20200915polestarlcafinala.pdf.

[48] Red Ensign Group. Yacht Code - Common Annexes. Technical Report January, 2019.

[49] SAFETY4SEAS. IMO adopts HFO ban for ships in Arctic . URL https://safety4sea.com/imo-adopts-hfo-ban-for-ships-in-arctic/.

[50] Silent Yachts. Vision & Technology. URL https://www.silent-yachts.com/vision-technology/.

[51] T.W.P. Smith, J.P. Jalkanen, B.A. Anderson, J.J. Corbett, J. Faber, S. Hanayama, E. O'keeffe, S. Parker, L. Johanasson, L. Aldous, and Others. Third IMO GHG Study. Technical report, International Maritime Organisation (IMO), London, 2014. URL www.imo.org.

[52] G.J. Suppes, S. Lopes, and C. W. Chiu. Plug-in fuel cell hybrids as transition technology to hydrogen infrastructure. *International Journal of Hydrogen Energy*, 29(4):369–374, 3 2004. ISSN 03603199. doi: 10.1016/S0360-3199(03)00216-7.

[53] Tesla. Impact Report 2019. Technical report, 2019. URL https://www.tesla.com/ns_videos/2019-tesla-impact-report.pdf.

[54] The Seabin Project. The Seabin V5 - For Cleaner Oceans, 2018. URL https://seabinproject.com/the-seabin-v5/.

[55] United Nations. The Paris Agreement, 2015. URL https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[56] P.T. Van Loon and P. Van Zon. From operational profile to hybrid propulsion. In *Proceedings of the 24th international HISWA symposium on yacht design and yacht construction. Amsterdam, The Netherlands*, volume 14, pages 1–13, 2016.

[57] B.O. Varga and F. Mariasiu. Indirect environment-related effects of electric car vehicle use. *Environmental Engineering and Management Journal*, 17(7):1591–1597, 2018. URL http://www.eemj.icpm.tuiasi.ro/;http://www.eemj.eu.

[58] B.O. Varga, A. Sagoian, and F. Mariasiu. Prediction of Electric Vehicle Range: A Comprehensive Review of Current Issues and Challenges. *Energies*, 12(5):946, 3 2019. ISSN 1996-1073. doi: 10.3390/en12050946.

[59] R.P. Verbeek, G. Kadijk, P. van Mensch, C. Wulffers, B. van den Beemt, F. Fraga, and A.D.A. Aalbers. *Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands*. Delft: TNO, 2011.

[60] Volkswagen. From the well to the wheel, 2019. URL https://www.volkswagenag.com/en/news/stories/2019/04/from-the-well-to-the-wheel.html#.

[61] Water Revolution Foundation. AIS data to a YETI Operational Profile. Presentation, 2021.

[62] H. Wu, G. Alberts, J. Hooper, and B. Walton. New market. New entrants. New challenges. Battery Electric Vehicles Contents. Technical report, Deloitte LLP, London, 2019.

[63] X. Wu, M. Aviquzzaman, and Z. Lin. Analysis of plug-in hybrid electric vehicles' utility factors using GPS-based longitudinal travel data. *Transportation Research Part C: Emerging Technologies*, 57:1–12, 8 2015. ISSN 0968090X. doi: 10.1016/j.trc.2015.05.008.

[64] yachtgala. Galapagos superyacht visitors. URL `https://www.galapagosyachtservices.com/index.php/component/sppagebuilder/94-galapagos-superyacht-visitors`.

[65] Y. Yang and A. Emadi. Hybrid and Plug-In Hybrid Electric Vehicles. In *Wiley Encyclopedia of Electrical and Electronics Engineering*, pages 1–22. John Wiley & Sons, Inc., 1 2013. doi: 10.1002/047134608x.w8191.

[66] G. Zubi, R. Dufo-López, M. Carvalho, and G. Pasaoglu. The lithium-ion battery: State of the art and future perspectives. *Renewable and Sustainable Energy Reviews*, 89:292–308, 6 2018. ISSN 18790690. doi: 10.1016/j.rser.2018.03.002.

A

Characteristic Speed Profiles

Van Loon and Van Zon [56] created a generic speed profile for yachts considering three speed regions - manoeuvring speeds, cruise speeds, and maximum speeds. It shows a high peak at cruising speeds and a very low use of maximum speeds. The manoeuvring to cruise speeds show a moderate sailing time share.

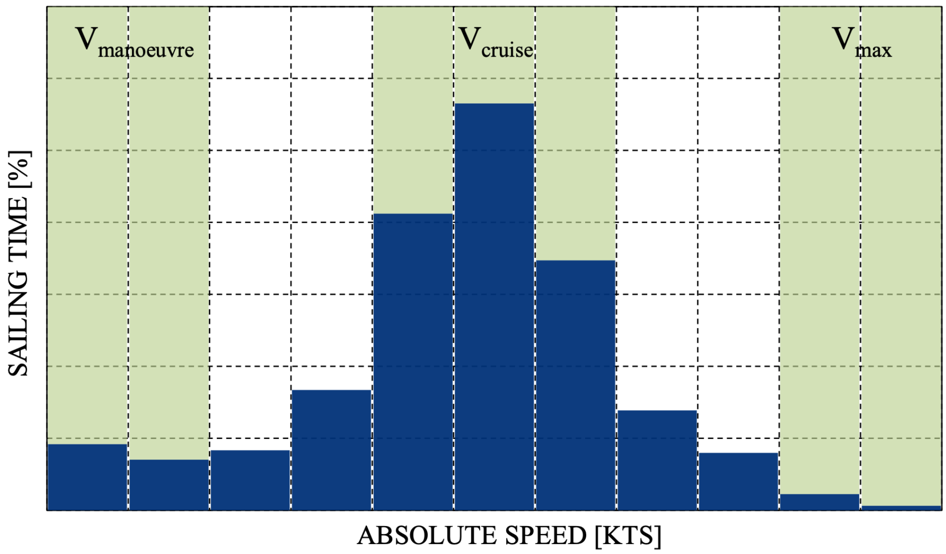


Figure A.1: Generic (absolute) speed profile. No axis are depicted to visualise a general speed.

Later on, Akershoek [3] made a deviation in operational profile-type. This resulted in a generic distribution being divided into a distribution for each of the three operational profiles. A similar distribution is observed. What is noticeable is that when the yacht changes from type A to C, the peak in the distribution shifts to higher speeds. This can be an effect of the more globally residence of that operational profile-type, resulting in trips of greater distances sailed at cruising speeds having a larger share in the distribution. This would underline the fact that yachts sail shorter distances at lower speeds than cruising speeds, when residing in the Mediterranean or Caribbean.

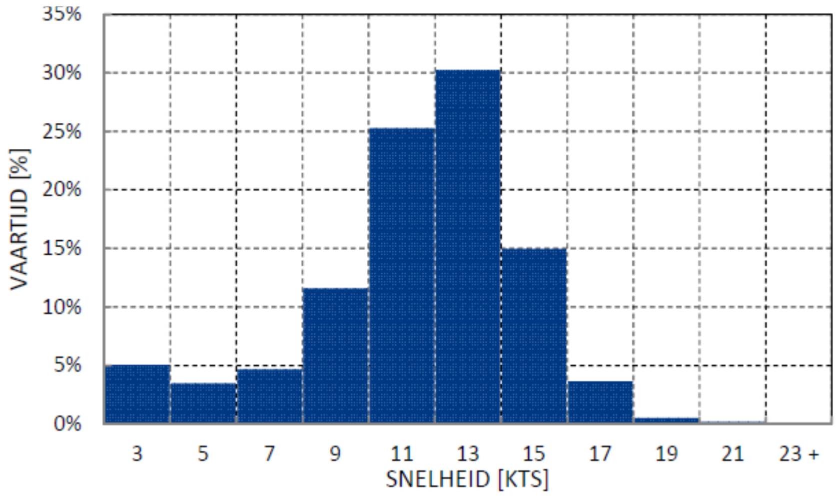


Figure A.2: Characteristic speed profile of type A.

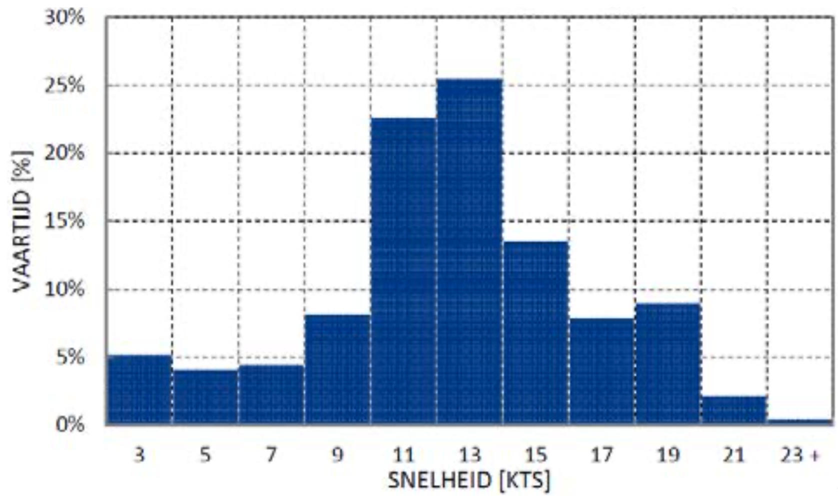


Figure A.3: Characteristic speed profile of type B.

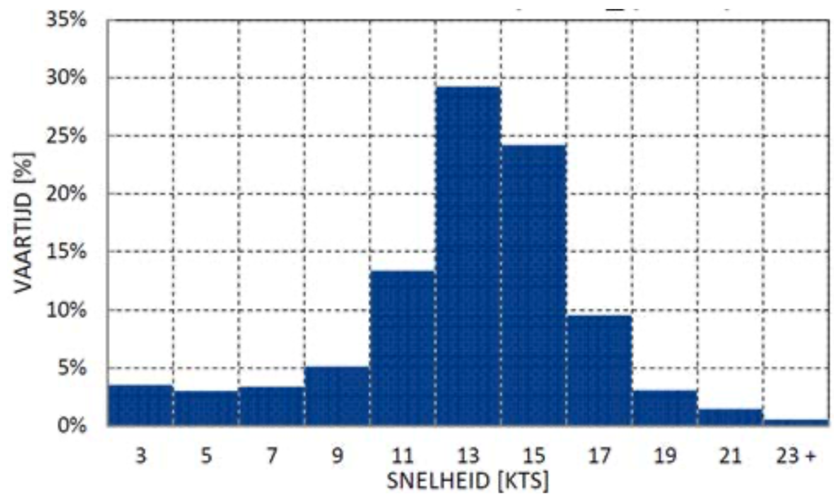


Figure A.4: Characteristic speed profile of type C.

B

Regression power equipment

In this appendix, the design parameters for a generator set and its associated power-dependent auxiliary equipment are determined. This is done respectively Sections B.1 and B.2. For this purpose, a dedicated data set has been created, which is presented in Section B.3.

B.1. Generator set

All diesel generators sets differ in size, volume, and power output among many other characteristics. Nevertheless, a single design parameter is needed to scale the generators in the design process. To obtain this value, a regression analysis is performed on the current market solutions. Accordingly, five renowned brands have been analysed, all of which supply diesel generator sets for the maritime industry. A diesel generator set consists of a high speed diesel diesel engine in line with a generator, as these are commonly used on a superyacht. The considered brands are Caterpillar, Cummins, MAN, MaK, and MTU. A review of the catalogues yielded a dataset of 73 high-speed diesel generators, which are listed in Table B.2 at the end of this chapter.

The required parameter is the power density of these generator sets, gravimetric or volumetric. Since available weight is the important design parameter in this study, the gravimetric power density ($\rho_{g,gens}$) in kilowatts per metric ton is chosen. In order to scale the volume of the generator set, the standard density (ρ_{gens}) is determined in metric tons per cubic meter. Simply averaging this data will not provide a correct value as a result. Therefore, the data are examined in two plots: one for power density versus power, and one for density versus power density. These are shown in Figure B.1 and B.3.

The figures show that the MaK generator sets have a significantly lower gravimetric power density than the other brands. Also, the Cummins generator sets have a significantly lower density, indicating a higher absorbed volume per ton than the other brands. Therefore, both brands are neglected in the further regression. A mathematical regression analysis to determine both design parameters proved to be impossible. The proposed solution is to place squares around the resulting data set and determine a constant mean of the design parameters. This procedure is illustrated in Figure B.2 and B.4.

This results in a gravimetric power density of $106 kWe/t$, and a uniform density of $0.67 t/m^3$.

The product of the generated current and system voltage is the apparent power, measured in VA (or kVA). The relation between apparent power and real power is the power factor ($pf = \cos\phi$). A non-optimised connection of the generator sets to the on-board electric grid causes a phase shift between the electrical sine waves of the two systems. This power factor indicates the utilisation of the electrical power generated - a power factor of 1 indicates no phase shift between the two and thus optimal utilisation, while a low power factor indicates a large phase shift and correspondingly poor utilisation. The power factor is generally assumed by the classification societies to be 0.8*, but in a well-designed electrical system this value can increase to values* ≥ 0.9. *In this study, the power factor of the classification societies is used.*

$$P = U \cdot I \cdot \cos\phi = U \cdot I \cdot 0.8 \tag{B.1}$$

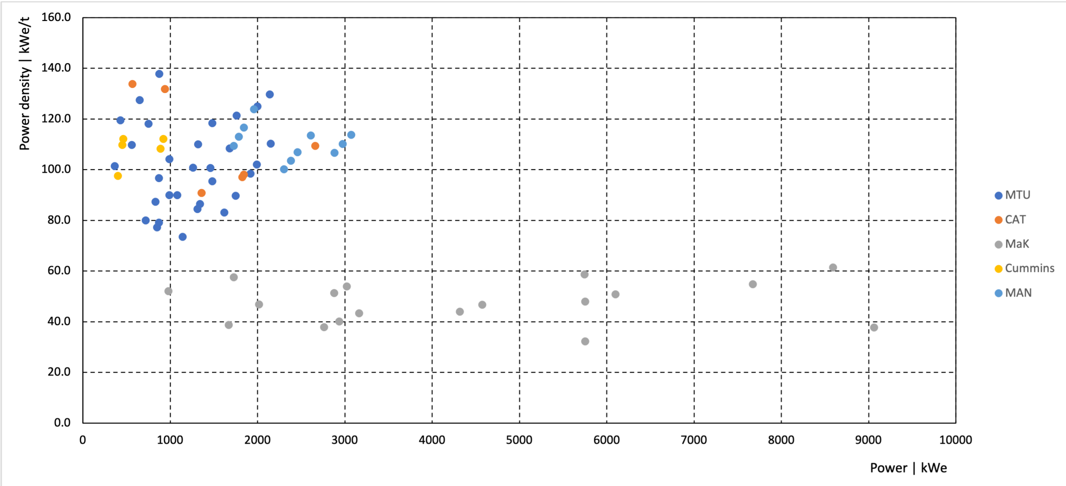


Figure B.1: The gravimetric power density of a generator set over the course of increasing generator set power.

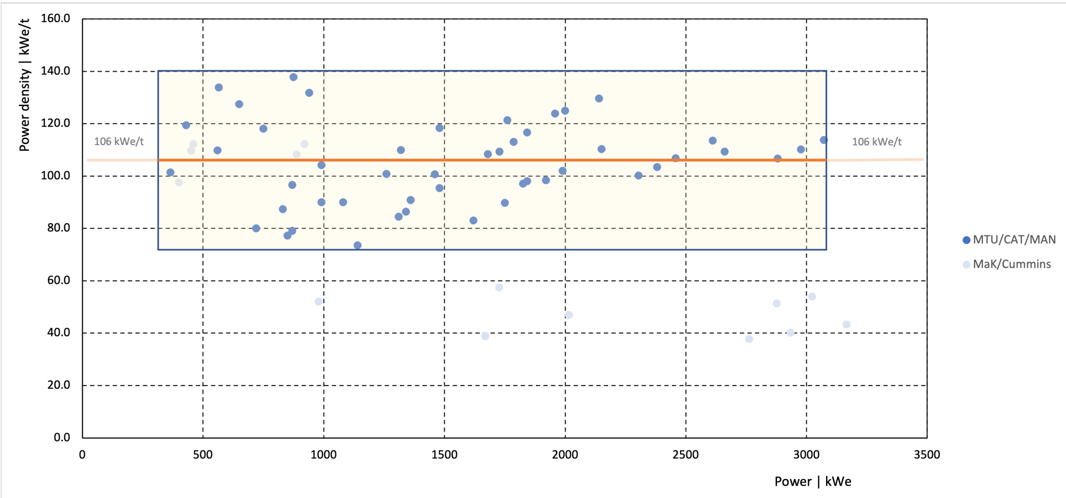


Figure B.2: The gravimetric power density of a generator set over the course of increasing generator set power.

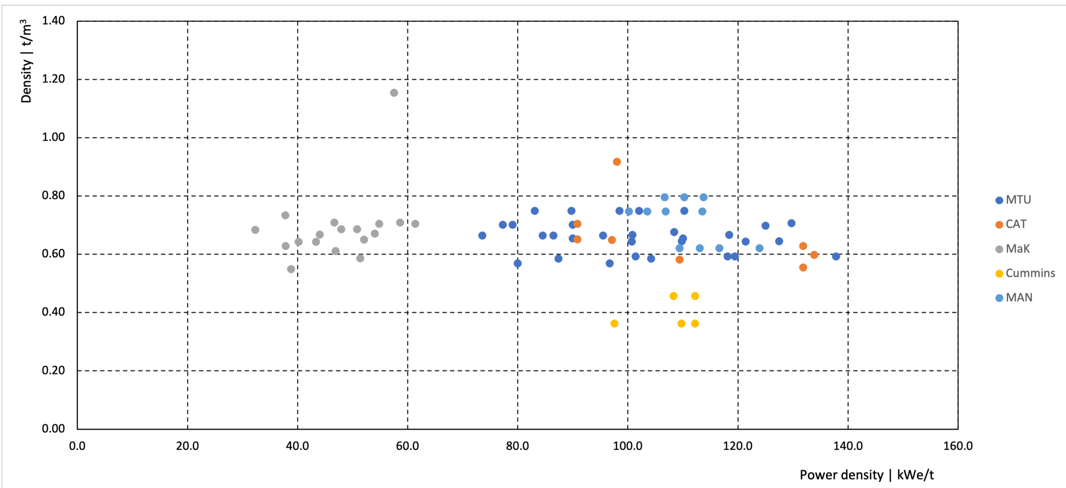


Figure B.3: The gravimetric power density of a generator set.

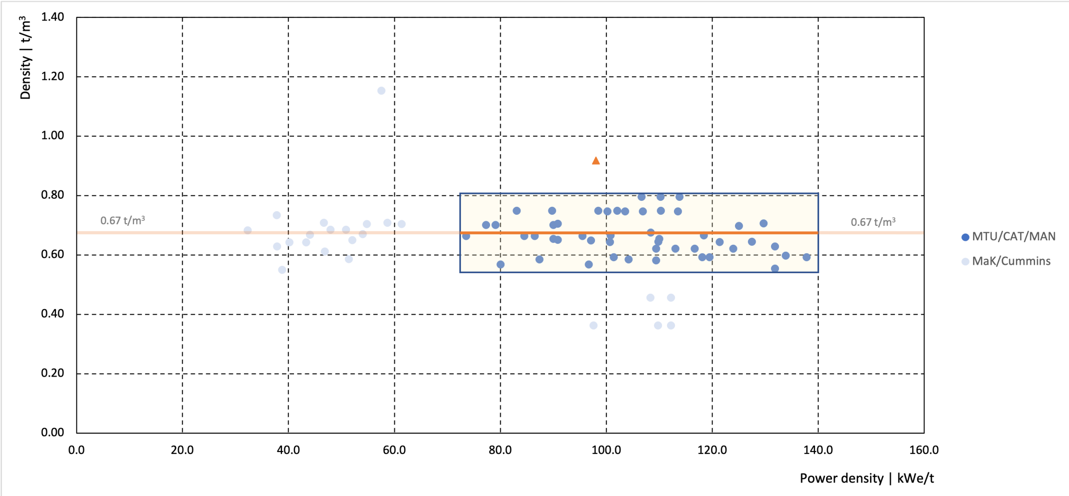


Figure B.4: The gravimetric power density of a generator set.

B.2. Auxiliary equipment

The design parameters for power dependent auxiliaries are composed of the mass and volume of the converters and the switchboard. A converter is required to convert the electrical power generated into the required DC voltage for which the installed switchboard is designed.

The switchboard is rated for the maximum electrical power resulting from the load balance, which is the combined maximum propulsive plus hotel power. Therefore, the power dependent auxiliary equipment scales with the maximum power in the system. In addition to the switchboard, which is already present in a diesel-electric configuration, an additional component is required to control the battery modules. Only this part of the switchboard is scaled. Additional service space must be considered as the equipment must be able to be maintained and/or operated by the crew.

To get representative values for the actual installed equipment, P. van der Veer[1] is asked what equipment is regularly installed on superyachts. He suggested ABB 's converters and switchboards as a high-end market solution. A review of their catalogs revealed the system parameters as shown in Table B.1. Both of ABB 's electrical devices are liquid cooled. This is similar to the battery considered in this study, making additional ventilation systems obsolete in this design. The service spaces are calculated with a path of 80cm between two opposing components.

Summing the different components for both densities gives a gravimetric power density ($\rho_{g,aux}$) of 0.00171 t/kWe and a volumetric density ($\rho_{V,aux}$) of 0.00565 m^3/kWe.

Table B.1: The power densities of the power-dependent auxiliary equipment.

Equipment	Power	Mass	Volume				Power density	
			H	W	D	Net	Gravimetric	Volumetric
	$[kW]$	$[kg]$	$[m]$	$[m]$	$[m]$	$[m]$	$[kg/kW]$	$[m^3/kW]$
Converter	790	244	1.89	0.45	0.94	0.80	0.31	0.00101
Service space	1580	0.00	1.89	0.80	0.45	0.68	0.00	0.00043
Switchboard	500	700	2.00	1.00	0.65	1.30	1.40	0.00260
Service space	1000	0.00	2.00	0.80	1.00	1.60	0.00	0.00160

[1]An electrical specialist at Royal van Lent Shipyards, Feadship Group.

B.3. Data generator sets

Table B.2: The created dataset of high-speed diesel generator sets.

Brand	Type	Volume $[m^3]$	Mass $[t]$	Density $[t/m^3]$	Electric power $[kWe]$	Gravimetric density $[kWe/t]$
MTU	8V 2000 M52B	6.1	3.6	0.59	365	101.4
MTU	8V 2000 M41B	6.1	3.6	0.59	430	119.4
MTU	12V 2000 M 51B	7.9	5.1	0.65	560	109.8
MTU	12V 2000 M41B	7.9	5.1	0.65	650	127.5
MTU	16V 2000 M51B	10.7	6.4	0.59	750	118.1
MTU	16V 2000M41B	10.7	6.4	0.59	875	137.8
MTU	8V 4000 M23F	15.8	9.0	0.57	720	80.0
MTU	8V 4000 M33F	16.2	9.5	0.58	830	87.4
MTU	12V 4000 M23F	18.3	12.0	0.65	1080	90.0
MTU	12V 4000 M33F	18.8	12.5	0.67	1260	100.8
MTU	16V 4000 M23F	22.5	14.5	0.64	1460	100.7
MTU	16V 4000 M33F	22.9	15.5	0.68	1680	108.4
MTU	8V 4000 M23S	15.8	9.0	0.57	870	96.7
MTU	8V 4000 M33S	16.2	9.5	0.58	990	104.2
MTU	12V 4000 M23S	18.3	12.0	0.65	1320	110.0
MTU	12V 4000 M33S	18.8	12.5	0.67	1480	118.4
MTU	16V 4000 M23S	22.5	14.5	0.64	1760	121.4
MTU	16V 4000 M33S	22.9	16.0	0.70	2000	125.0
MTU	16V 4000 M43S	23.4	16.5	0.71	2140	129.7
MTU	MG08V4000M24S	15.7	11.0	0.70	850	77.3
MTU	MG08V4000M23S	15.7	11.0	0.70	870	79.1
MTU	MG08V4000M33S	15.7	11.0	0.70	990	90.0
MTU	MG12V4000M24S	23.3	15.5	0.66	1140	73.5
MTU	MG12V4000M23S	23.3	15.5	0.66	1310	84.5
MTU	MG12V4000M34S	23.3	15.5	0.66	1340	86.5
MTU	MG12V4000M33S	23.3	15.5	0.66	1480	95.5
MTU	MG16V4000M24S	26.0	19.5	0.75	1620	83.1
MTU	MG16V4000M23S	26.0	19.5	0.75	1750	89.7
MTU	MG16V4000M34S	26.0	19.5	0.75	1920	98.5
MTU	MG16V4000M33S	26.0	19.5	0.75	1990	102.1
MTU	MG16V4000M43S	26.0	19.5	0.75	2150	110.3
CAT	C18 ACERT	7.1	4.2	0.60	565	133.9
CAT	C32 ACERT IMO II	12.9	7.1	0.55	940	131.8
CAT	C32 ACERT IMO III	11.3	7.1	0.63	940	131.8
CAT	3512B	21.2	15.0	0.70	1360	90.8
CAT	3512C	23.0	15.0	0.65	1360	90.8
CAT	3516B	29.0	18.8	0.65	1825	97.1
CAT	3516C	20.5	18.8	0.92	1843	98.0
CAT	C175-16	41.8	24.3	0.58	2660	109.4
MaK	M 20 C	28.9	18.8	0.65	979	52.1
MaK	M 20 C	26.0	30.0	1.15	1726	57.5
MaK	M 25 C	78.2	43.0	0.55	1669	38.8
MaK	M 25 C	95.6	56.0	0.59	2877	51.4
MaK	M 25 E	70.3	43.0	0.61	2016	46.9
MaK	M 25 E	83.5	56.0	0.67	3024	54.0
MaK	M 32 C	116.1	73.0	0.63	2762	37.8
MaK	M 32 C	146.7	98.0	0.67	4316	44.0
MaK	VM 32 C	175.1	120.0	0.69	5754	48.0
MaK	VM 32 C	198.7	140.0	0.70	7672	54.8
MaK	M 32 E	113.5	73.0	0.64	3165	43.4

Table B.2 continued from the previous page

Brand	Type	Volume	Mass	Density	Electric power	Gravimetric density
MaK	M 32 E	138.4	98.0	0.71	5747	58.6
MaK	VM 32 E	175.1	120.0	0.69	6099	50.8
MaK	VM 32 E	198.7	140.0	0.70	8593	61.4
MaK	M 34 DF	113.6	73.0	0.64	2934	40.2
MaK	M 34 DF	138.4	98.0	0.71	4574	46.7
MaK	M 43 C	260.5	178.0	0.68	5754	32.3
MaK	M 43 C	326.9	240.0	0.73	9063	37.8
Cummins	K19-CP	11.3	4.1	0.36	400	97.6
Cummins	K19-CP	11.3	4.1	0.36	450	109.8
Cummins	K19-CP	11.3	4.1	0.36	460	112.2
Cummins	K38-CP	18.0	8.2	0.46	888	108.3
Cummins	K38-CP	18.0	8.2	0.46	920	112.2
MAN	12V175D-MEM	25.4	15.8	0.62	1728	109.4
MAN	12V175D-MEL	25.4	15.8	0.62	1843	116.6
MAN	12V175D-MEV	25.4	15.8	0.62	1786	113.0
MAN	12V175D-MEV	25.4	15.8	0.62	1958	123.9
MAN	16V175D-MEM	30.8	23.0	0.75	2304	100.2
MAN	16V175D-MEL	30.8	23.0	0.75	2458	106.9
MAN	16V175D-MEV	30.8	23.0	0.75	2381	103.5
MAN	16V175D-MEV	30.8	23.0	0.75	2611	113.5
MAN	20V175D-MEM	33.9	27.0	0.80	2880	106.7
MAN	20V175D-MEL	33.9	27.0	0.80	3072	113.8
MAN	20V175D-MEV	33.9	27.0	0.80	2976	110.2

C

Regression energy equipment

C.1. Battery

All Lithium-ion batteries differ in size, volume, and storage capacity among many other characteristics. Yet, design parameters are required to scale the batteries in the design process. The largest discrepancy among Lithium-ion batteries is expected in a volumetric sense. Therefore, the volumetric energy density and the normal density are studied in this appendix.

An internal dataset of DVNA consisting of 73 different batteries is used for this purpose. A division is made between ready for use and remaining market reference products. The ready for use products are maritime certified products, which can be purchased and installed directly. An additional split is made between maritime modules and racks.

The ready for use batteries are shown in Table C.3 and are sorted by their volumetric energy density. In the density are the depth-of-discharge (DoD) and end-of-life (EoL) marge taken into account. P. van der Veer[1] explained that the values of 75% and 90% are regularly used for battery modules installed on superyachts. The DoD corresponds to a minimum controlled state-of-charge (SoC) of the batteries of 20%, and a maximum SoC of 95%. The EoL marge takes the ageing, and therefore the reduction in usable capacity, of batteries into account. As a result, the battery will not immediately have a lower capacity than it was designed for when the first degradation occurs.

The results show that modules have a significantly higher density than racks. Therefore, it is chosen to only consider the maritime modules in this study. An exponential regression analysis was performed in Figure C.1 to determine any correlation between both energy density and density. This found relation is shown in the figure, however, this relation is only valid for single modules. In the studied concept, numerous modules are potentially installed. It is therefore chosen to consider only a single module type: the Akasol 9AKM 150 CYC [2]. The Akasol battery is chosen as it is a more renowned brand than E3, it is liquid cooled, and more design parameters were available. The design parameters are shown in Table C.1. It shows a gravimetric energy density ($\rho_{g,batt}$) of $183 kWh/t$ and a volumetric energy density ($\rho_{V,batt}$) of $124 kWh/m^3$.

Table C.1: Battery characteristics of the Akasol 9AKM 150 CYC.

Capacity	**Volume**				**mass**	**Energy density**		**C-rate**	**Lifetime**
Net	H	W	D	Net	Net	Gravimetric	Volumetric	Continuous	End
$[kWh]$	$[m]$	$[m]$	$[m]$	$[m^3]$	$[kg]$	$[kWh/t]$	$[kWh/m^3]$	$[-]$	$[Cycles]$
98.0	1.7	0.7	0.3	0.36	535	183	124	1.00	4000

[1] An electrical specialist at Royal van Lent shipyards, Feadship group.

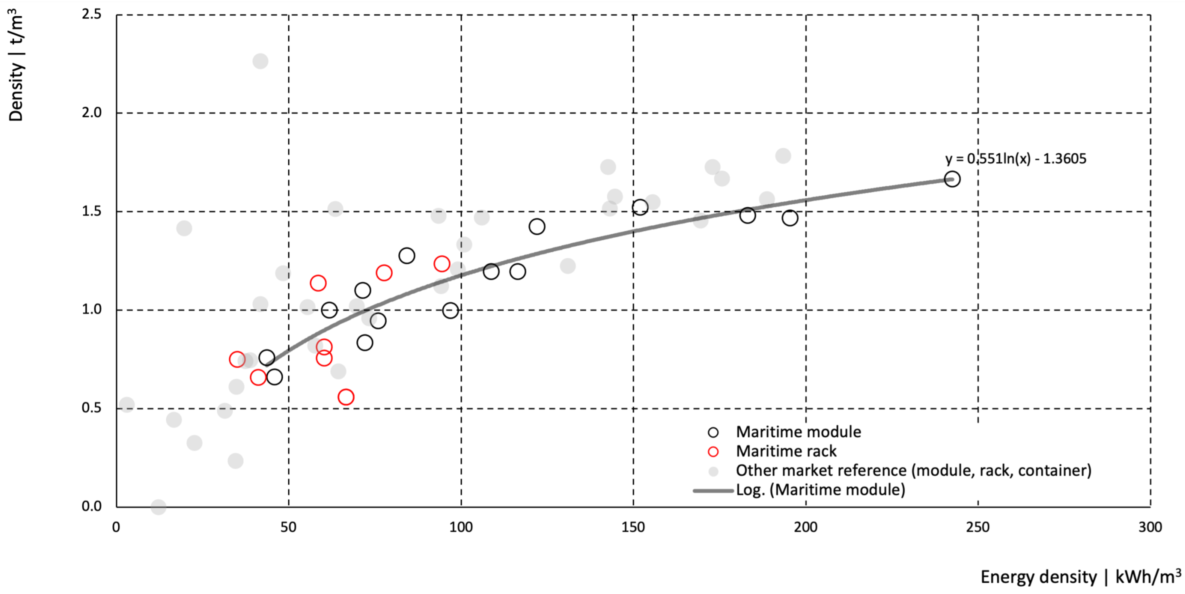


Figure C.1: The gravimetric energy density of a maritime Battery as ESS, compared to the density itself.

C.2. Auxiliary equipment

The auxiliary equipment of the considered battery, which is energy capacity-dependent, is the cooling installation. This cooling equipment is the heat exchanger and the accompanying required piping. This equipment ensures that the battery module maintains within its operating temperature window. The required design parameters of this component are therefore the energy dependent mass and volume. Additional service spaces must be taken into account, as the equipment must be able to be maintained and/or operated by the crew.

The dimensions for a single heat exchanger are estimated by P. van der Veer, see Table C.2. A single heat exchanger of this size is able to cool ten Akasol units. Therefore, the estimated dimension are divided by the energy capacity of ten units to obtain the design parameters. The piping is taken into account by adding an extra $10cm$ in front of the Akasol units, with the height and width equal to the battery itself. The service spaces are the remaining auxiliary equipment. A favourable characteristic of the considered battery is that service spaces are only required at the front of the battery. These areas are therefore taken into account by stacking three modules on top of each other and adding a path of $80cm$ between two opposing stacks of three.

It is an advantage that the energy capacity per module is known in advance. This makes it possible to calculate a dimensionless packing factor instead of a density. The resulting packing factors for mass (PF_m) and volume (PF_V) are respectively 1.004 and 1.203.

Table C.2: The energy densities of the energy-dependent auxiliary equipment.

Equipment	Capacity	Mass	Volume				Energy density	
			H	W	D	Net	Gravimetric	Volumetric
	$[kWh]$	$[kg]$	$[m]$	$[m]$	$[m]$	$[m^3]$	$[kg/kWh]$	$[m^3/kWh]$
Heat exchanger	980	10	0.60	0.30	0.20	0.04	0.010	0.00004
Piping	98	2	0.70	0.30	0.10	0.02	0.020	0.00021
Service space	588	0	2.10	0.80	0.30	0.00	0.000	0.00086

C.3. Data battery modules

Table C.3: The design parameters and energy densities of the ready for use battery dataset.

Brand	Type	Level	Energy	Mass	Volume	Density	Energy density		EoL	DoD
							Gravimetric	Volumetric	75%	90%
			$[kWh]$	$[kg]$	$[m^3]$	$[t/m^3]$	$[Wh/kg]$	$[kWh/m^3]$	$[kWh/m^3]$	$[kWh/m^3]$
E3	DC mod	Module	5.4	25.0	0.02	1.67	216	359	270	243
E3	DC rack B	Module	323.4	1640.0	1.12	1.47	197	290	217	195
Akasol	9AKM 150 CYC	Module	98.0	535.0	0.36	1.48	183	271	203	183
Nidec	Nidec - 1	Module	6.5	44.0	0.03	1.52	148	225	169	152
Akasol	Akasystem	Module	99.0	780.0	0.55	1.42	127	181	136	122
XALT	F960-0009	Module	11.1	77.0	0.06	1.20	144	173	129	116
KOKAM	Type 1 for Marine	Module	10.4	77.0	0.06	1.20	135	161	121	109
Torqeedo	i3	Module	40.0	278.0	0.28	1.00	144	144	108	97
PBES	Energy 88	Module	8.8	90.0	0.07	1.28	98	125	94	84
Nidec	Nidec -2	Module	100.0	840.0	0.89	0.94	119	112	84	76
EST-Floattech	Green Orca	Module	10.5	82.0	0.10	0.83	128	107	80	72
SAFT	Seanergy Module	Module	3.8	39.5	0.04	1.10	96	106	79	71
PowerTech	PowerRack	Module	2.6	28.0	0.03	1.00	91	91	69	62
Torqeedo	i8	Module	10.0	97.0	0.15	0.66	103	68	51	46
Aentron	Type F	Module	10.2	120.0	0.16	0.76	85	65	49	44
XALT	XPAND XRS-2	Module		100.8	0.09	1.19				
Nidec		Rack	112.1	990.0	0.80	1.24	113	140	105	94
Becker Marine Systems	Cobra Compact Battery Rack	Rack	92.0	950.0	0.80	1.19	97	115	86	78
Corvus	Dolphin 7 Modules	Rack	77.0	436.0	0.78	0.56	177	99	74	67
Corvus	Dolphin 4 packs	Rack	308.0	1743.0	3.12	0.56	177	99	74	67
Corvus	Blue Whale (6 strings)	Rack	3612.0	32870.0	40.41	0.81	110	89	67	60
Corvus	Blue Whale (4x6 strings)	Rack	14448.0	122200.0	161.63	0.76	118	89	67	60
Corvus	Orca (vertical)	Rack	124.0	1628.0	1.43	1.14	76	87	65	59
PBES	Energy 88	Rack	88.0	950.0	1.44	0.66	93	61	46	41
SAFT	Saenergy Rack	Rack	52.0	750.0	1.00	0.75	69	52	39	35

D

Shore Power Questionnaire

Based on the gap in literature and the sector specific nature of the information, it is chosen to conduct a questionnaire among marinas globally to determine these topics. The questionnaire is conducted in cooperation with Water Revolution Foundation (WRF), as DVNA has a good relation with them and WRF has valuable connections in the world wide marina industry. Due to competition clauses, DVNA or Feadship are not mentioned. WRF wanted to obtain a lot much more insight into this industry via the questionnaire, for the sake of completeness, the entire questionnaire is attached.

D.1. Marina questionnaire

This questionnaire has been created by The Water Revolution Foundation. The information from this questionnaire will help to assess the current and future environmental impacts of both the yachts of interest as well as marinas.

For the open short and long-form answers please answer to the best of your ability, but if required, put unknown/unsure. Some questions overlap (for example, 2 questions are the exact same but with different units) so you do not need to fill out every question in these cases. Educated guesses are also fine. Please get in contact if you have any queries.

All answers you can give us are greatly appreciated and will help with our research.

The Water Revolution Foundation will report its results from this on our website.

Email: megan@waterrevolutionfoundation.org

* Obligatory

1. Where is the marina located? * City or region plus country is preferred.

Capacity of the Marina
This section is to collect information on the profile of usage of the marina of different size yachts with their varying power demands, and what exactly this power consumption tends to be.

2. How many unique yachts (LOA > 30m) can the marina accommodate in a typical year? *
3. What is the typical duration of a stay in your marina? * Please answer in days.
4. What share of these yachts are in the following length categories? Please add all shares that apply and educated guesses also suffice.
   30-39m / 40-49m / 50-69m / 70-109m / 110m and over
5. What share of these yachts are in the following Gross Tonnage categories? Please add all shares that apply and educated guesses also suffice. If you do not have this information, please leave it empty. If the previous question is already answered, you may leave this unanswered.
   up to 299GT / 300-399GT / 400-499GT / 500-999GT / 2000-2999GT / 3000GT and over
6. What is the marina's maximum size yacht it can accommodate, in length and/or GT? Please add the unit in your answer.

7. How many maximum size, as stated in the previous question, slips/berths does the marina have?
8. What is the percentage occupancy of this maximum size in a typical year?
9. How many instances in a typical year do yachts have to anchor outside the marina as they are too large to have a berth?
10. During the time a yacht is accommodated in your marina, what share of that time is it connected to shore power? Please add all shares that apply and educated guesses also suffice.
    30-39m / 40-49m / 50-69m / 70-109m / 110m and over
11. Is there any possible explanation in why a specific size yacht is connected to the shore power for a longer/shorter period of time? Please include the size range and unit in your answer.Are you looking to encourage an increase in the time a yacht is connected to shore power? Please include in your answer what means you look to achieve this if so.
12. How in your experience do yachts choose to use shore power or not, when accommodated at a marina? What are you looking to do to increase the time yachts are connected to shore power.
13. What is the average weekly consumption of all the accommodated yachts combined? * Please answer in kWh per week, or state units.
14. What is the maximum weekly consumption of all the accommodated yachts combined in peak season? * Please answer in kWh per week, or state units.

Details of the Available Berths/Slips
This section is to understand the power availability specific to the different berths available within the marina.

15. Do the berths/slips in the marina have a set power availability depending on the size of the berth/slip?
    (a) Yes - a large sized yacht has a different shore power connection than a small sized yacht
    (b) No - a large sized yacht has a similar shore power connection as a small sized yacht
16. If so, what are the power availabilities per berth size that the marina offers?
    Please provide the power availability for all length ranges as in previous questions to the best of your capability. Educated guesses also suffice. Answer by using only one of the following ranges 30-39m, 40-49m, 50-69m, 70-109m, 110m+ or 0-299GT, 300-399GT, 400-499GT, 500-999GT, 999-1999GT, 2000-2999GT, 3000GT+.
17. If not, what are the power options supplied at the marina?
18. Does the marina offer quick charging points specifically for electric/hybrid vessels such as electric tenders? *
    (a) Yes - Installed charging points
        i. How many quick charging points are there in the marina? *
        ii. What power can a single charging point supply? * Please answer in kW.
    (b) No - Not looking to install
        i. Why are you not looking to install quick charging? *
    (c) No - Looking to install in the future
        i. Why are you looking to install quick charging? *
        ii. How many quick charging points are you looking to install? *
        iii. What is the preferred power supply by a single quick charging point? * Please answer in kW.

Marina Power Supply Section
In this section, please provide information on the power supply to the marina that is subsequently used to supply shore power to yachts.

19. What share of the following sources is the marina connected to for its shore power? * Please add all shares that apply and educated guesses also suffice.
    Unknown supply (e.g: local power grid) / Generated onsite (e.g: fuel generators) / Renewable generated onsite (e.g: solar panels) / Specific supply (e.g: nuclear power plant) / Specific renewable supply (e.g: wind farm)
20. What is the power supply received by the marina? * Please answer in kW.
21. Is that power supply sufficient to comply with demand? Or is it a cause for instability? *
    (a) Yes - It suffices
    (b) No - It is a cause for instability
22. Is that power supply likely to change in the future? *
    (a) Yes - It is expected to change
    (b) No - It is not expected to change

23. Why is the power supply likely to change / not change in the future?
24. What is the price per unit of supplied power? Please add the currency and unit of charge. e.g. €0.25 per kWh.
25. What is the price for a litre of diesel at the marina? Please add the currency of charge. e.g. €1 per litre.

Sustainability of the Marina
Please provide in the following section details on the sustainability measures the marina is currently taking or looking to take, including the amount of renewable energy used by the marina.

26. What kind of measures has the marina taken to reduce its environmental impact? * Select all that apply or use "other" to explain existing marina programmes.
    - Creating and applying a more sustainable business policy
    - Used more sustainable technology, e.g. more efficient machinery
    - Used more sustainable resources, e.g. sustainable sourced water supply, or biodegradable cleaning supplies
    - Used more sustainable processes within the marina, e.g. improved waste management
    - None of the above
    - Other: ...
27. Is the marina expected to increase the share of the supplied energy to a more renewable energy share? * e.g. The marina now uses a share of 30% sustainable and 70% general. This increases to 60% sustainable and 40% general.
    (a) Yes - Our energy is becoming more renewable
    (b) No - Our energy is maintains the same source
    (c) n/a
28. Please specify the desired distribution. e.g. A 4 is 40% renewable and 60% general.
29. Why are you looking to change this? Select all that apply
    - To improve the social image of the company
    - To reduce the marina's environmental impact
    - Because of business benefits
    - Forced by regulations
    - Because of client demands
    - Government incentive
    - None of the above
    - Other: ...

Future section
This section assesses the likely trends that marinas will see in the future related to their power supply and demand and the reasons for these.

26. Is the marina's available shore power for yachts expected to increase? *
    (a) Yes - It is expected to increase
    (b) No - It is expected not to increase
    (c) Unsure
27. Is this likely to occur before or after demand has increased? *
    (a) Before
    (b) After
    (c) n/a
28. Is this likely to occur upon own initiative or by pressure from the local government/community?
    (a) Upon own initiative
    (b) By pressure from the local government
    (c) By pressure from the local community
    (d) Other: ...
29. What trend does the marina expect to happen regarding the shore power? * Please select all that apply
    - A reduction in available shore power demand
    - An increase in available shore power demand
    - No change in available shore power demand
    - A reduction in amount of power for the size of vessel consumed
    - An increase in amount of power for the size of vessel consumed

- No change in amount of power for the size of vessel consumed
- A change to a more renewable source of power
- A change to a more general source of power
- No change in the source of power
- Other: ...

Thank you for your participation. Your answers are saved. The Water Revolution Foundation greatly appreciates your input on the road to a more sustainable yachting industry.

D.2. Results

The results of the questionnaire for marinas are discussed qualitatively per section, except for the available shore power. This is discussed quantitatively, as these numbers determine the available shore power connection. The qualitatively discussed results are the results of the "Sustainability of the Marina" and the "Future section".

The survey showed that all marinas expect an increase in shore power demand, therefore they want to expand their shore power infrastructure. This is mostly on their own initiative - or induced by market demand - and rarely due to community or government pressure. The marinas themselves expect that this trend is industry-wide. In addition, marinas intend to make their own power supply more sustainable, either by generating sustainable electricity on site or by purchasing more sustainable electricity. This change is induced by government incentives and regulations, or to reduce their environmental impact and improve their corresponding social image. As a result, available shore power for superyachts will increase while becoming more sustainable.

The available shore powers resulting from the marina questionnaire are shown in Table D.1. This dataset was deemed too small, therefore an online research into the available shore power was conducted. This increased the available data from 13 to 36 marinas around the globe. These were subdivided into the areas where yachts reside: Mediterranean Sea, Adriatic Sea, Caribbean Sea, and remaining areas. This resulted in the power per area shown in Tables D.2 to D.5.

Multiplying the specified current and voltage of a single-phase direct current (DC) circuit directly gives the electrical power. However, this is not the power of a three-phase alternating current (AC) circuit. This circuit consists of three phases, all of which have the same line power as the single-phase DC circuit. But, these three powers may not be summed to get the total power. A correction must be made because the phase angles between the three different phases differ by 120 degrees, so that the three phases contribute only a factor $\sqrt{3}$ to the total power. This principle is illustrated in Figure D.1, where U, W , V are the lines, line (L) to zero (N) are the line powers, and line to line are the phase powers.

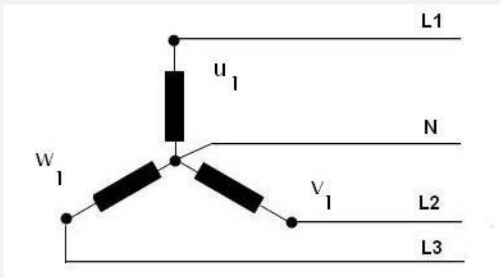


Figure D.1: The principle of a three-phase AC circuit.

$$P = U \cdot I \cdot \sqrt{3} \tag{D.1}$$

Table D.1: The resulting shore powers out of the marina shore power questionnaire.

Place	**Country**	**Current** [A]	**Voltage** [V]	**Frequency** [Hz]	**Power** [kW]
Barcelona	Spain		380	50	1633
Tivat	Montenegro	1000	380	50	658
La Spezia	Italy	700	380	50	461
Šibenik	Croatia	600	380	50	395
Genova	Italy	600	380	50	395
N/A	N/A	600	380	60	395
Monaco	Monaco	400	380	50	263
Monaco	Monaco	400	380	50	263
Simpson Bay	Saint Maarten	200	480	60	166
Pesaro	Italy	250	380	50	165
Salerno	Italy	250	380	50	165
Rodney bay	Saint lucia	200	220	60	76
Saint Thomas	Virgin Islands	50	480	60	33
Average					**390**

Table D.2: The resulting shore powers in the Adriatic Sea.

Place	**Country**	**Current** [A]	**Voltage** [V]	**Frequency** [Hz]	**Power** [kW]
Bodrum	Turkey	1400	380	50	921
Tivat	Montenegro	1000	380	50	658
Portonovi	Montegro	630	380	50	415
Šibenik	Croatia	600	380	50	395
Dubrovnik	Croatia	125	380	50	82
Average					**494**

Table D.3: The resulting shore powers in the Caribbean Sea.

Place	**Country**	**Current** [A]	**Voltage** [V]	**Frequency** [Hz]	**Power** [kW]
Caroline bay	Bahamas	200	480	60	166
Bocas Del toro	Panama	200	480	60	166
Christophe Harbou	Saint Kitts	200	480	60	166
Rodney bay	Saint lucia	200	480	60	166
Simpson Bay	Saint Maarten	200	480	60	166
Santa Marta	Columbia	100	480	60	83
Blue haven	Providenciales	100	480	60	83
Rodney bay	Saint Lucia	100	480	60	83
Simpson bay	Saint Maartin	100	480	60	83
Simpson bay	Saint Maartin	100	480	60	83
Charlotte Amalie	Saint Thomas	100	480	60	83
Red Hook	Virgin Islands	50	480	60	42
Saint Thomas	Virgin Islands	50	480	60	33
Average					**109**

Table D.4: The resulting shore powers in the Mediterranean Sea.

Place	**Country**	**Current** [A]	**Voltage** [V]	**Frequency** [Hz]	**Power** [kW]
Barcelona	Spain		380	50	1633
Sete	france	2000	380	50	1316
Malaga	Spain	2000	380	50	1316
Barcelona	Spain	1250	380	50	823
La Spezia	Italy	700	380	50	461
Genova	Italy	600	380	50	395
Monaco	Monaco	400	380	50	263
Monaco	Monaco	400	380	50	263
Saint Tropez	France	250	380	50	165
Pesaro	Italy	250	380	50	165
Salerno	Italy	250	380	50	165
Porto cervo	Sardinia	250	380	50	165
Average					**594**

Table D.5: The resulting shore powers in remaining areas.

Place	**Country**	**Current** [A]	**Voltage** [V]	**Frequency** [Hz]	**Power** [kW]
Dubai	UAE	1600	400	50	1109
Miami	USA	800	480	60	665
Fort lauderdale	USA	1000	480	60	658
N/A	N/A	600	380	60	395
Fort lauderdale	USA	200	480	60	132
London	England	125	380	50	82
Average					**541**

E

Design Figures

In this appendix, the different resulting design figures are shown. The figures are grouped per yacht. Per concept version, the following figures are presented:

- The speed-power curve
- The resulting CDF with potential impacts
- The Impact on operational profile

The first figures are shown on the next page.

E.1. Yacht-S

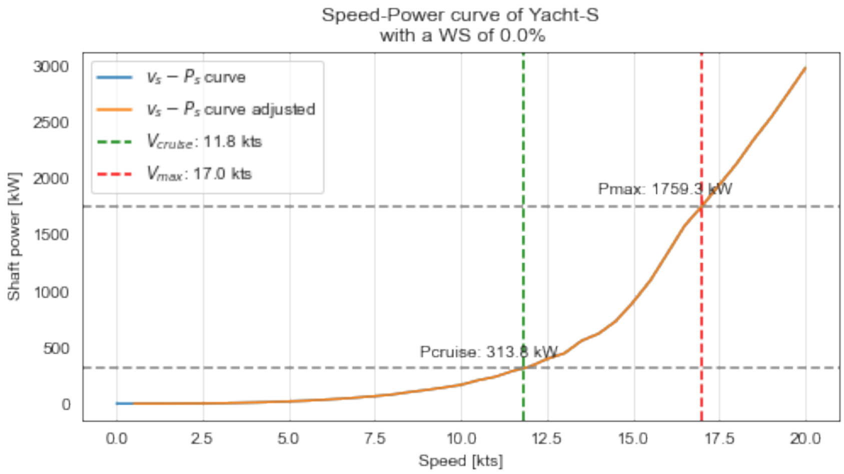


Figure E.1: The adjusted speed power curve for Yacht-S with a weight-share addition of 0.0%.

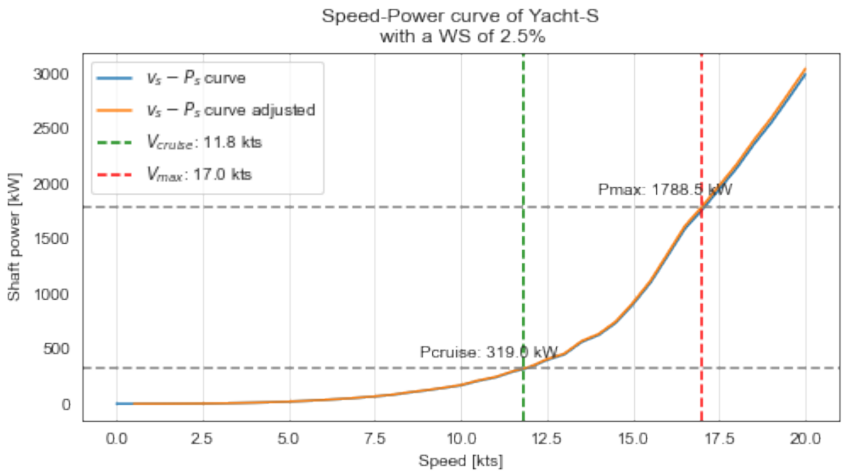


Figure E.2: The adjusted speed power curve for Yacht-S with a weight-share addition of 2.5%.

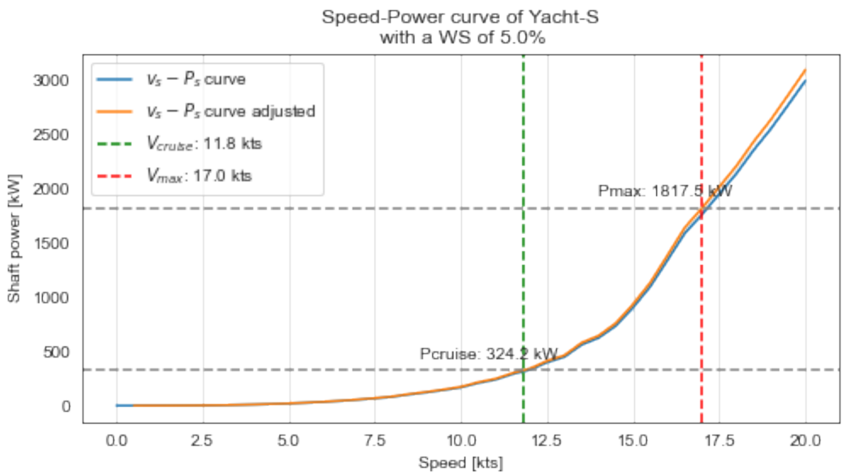


Figure E.3: The adjusted speed power curve for Yacht-S with a weight-share addition of 5.0%.

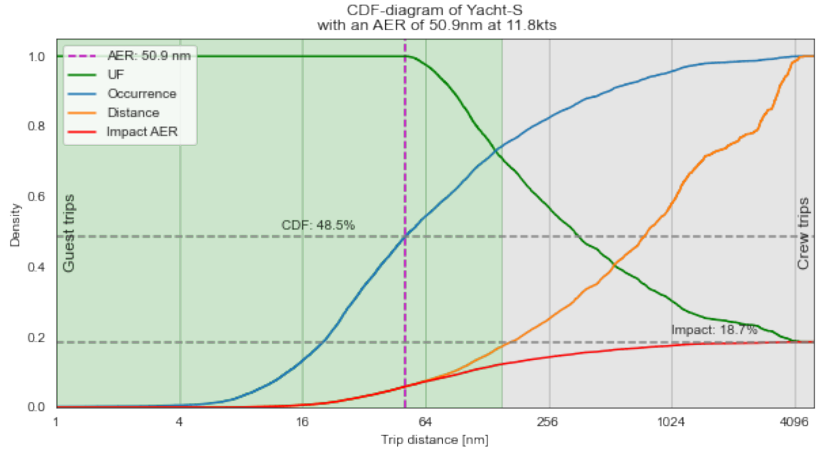


Figure E.4: The CDF of Yacht-S version 1.

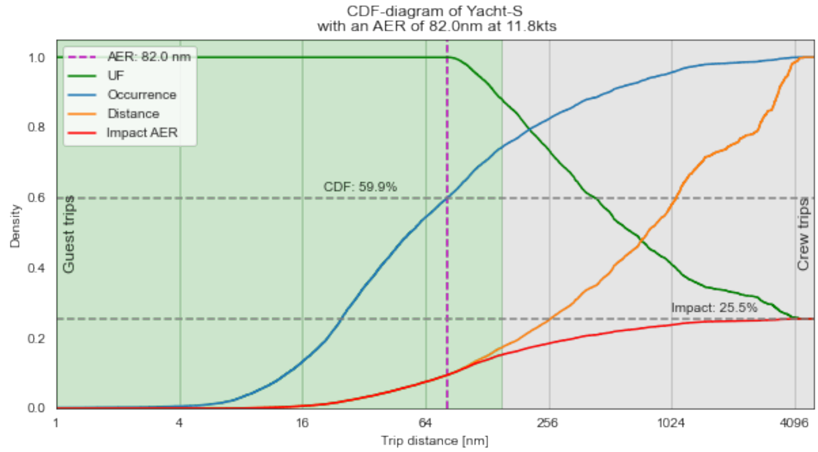


Figure E.5: The CDF of Yacht-S version 2.

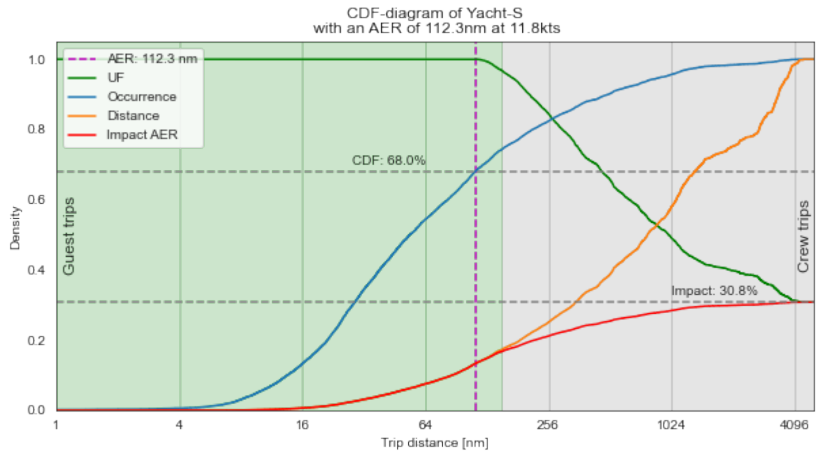


Figure E.6: The CDF of Yacht-S version 3.

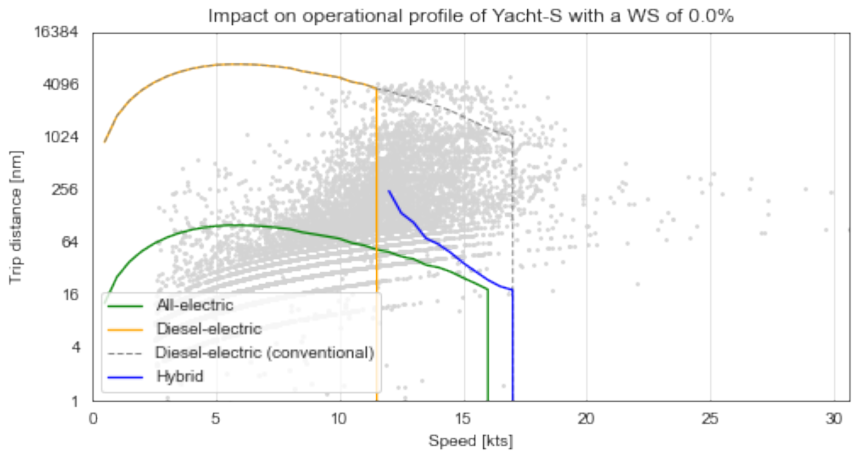


Figure E.7: The impact on the operational profile of Yacht-S with a weight-share addition of 0.0%.

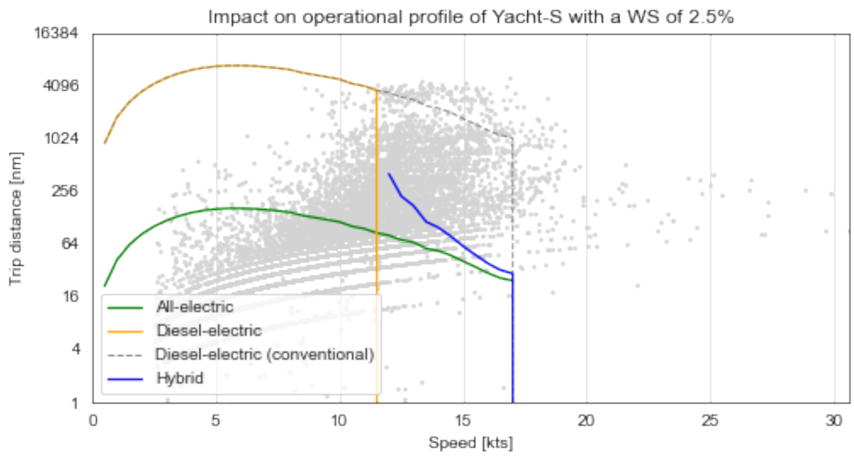


Figure E.8: The impact on the operational profile of Yacht-S with a weight-share addition of 2.5%.

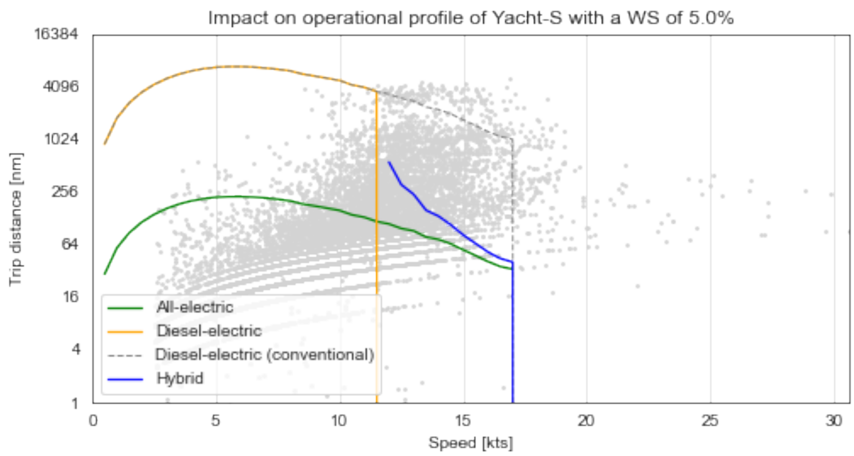


Figure E.9: The impact on the operational profile of Yacht-S with a weight-share addition of 5.0%.

E.2. Yacht-M

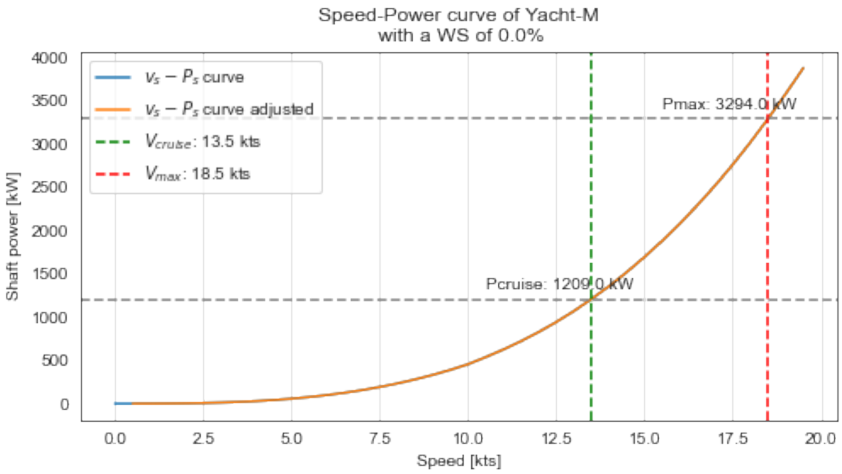


Figure E.10: The adjusted speed power curve for Yacht-M with a weight-share addition of 0.0%.

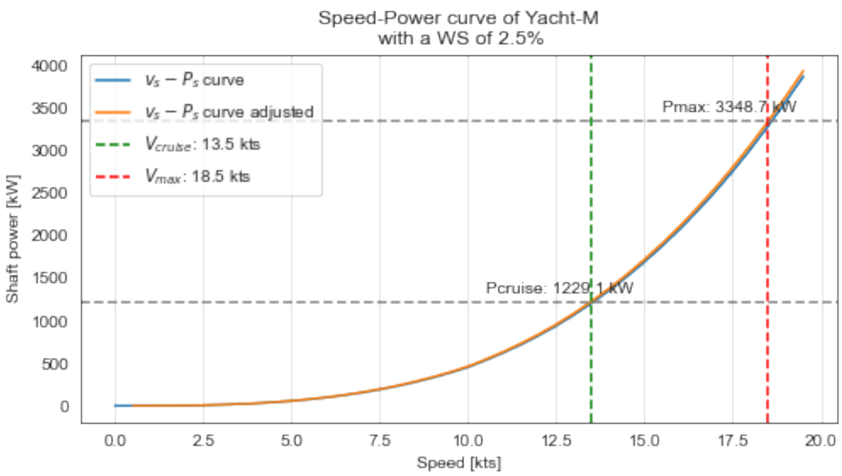


Figure E.11: The adjusted speed power curve for Yacht-M with a weight-share addition of 2.5%.

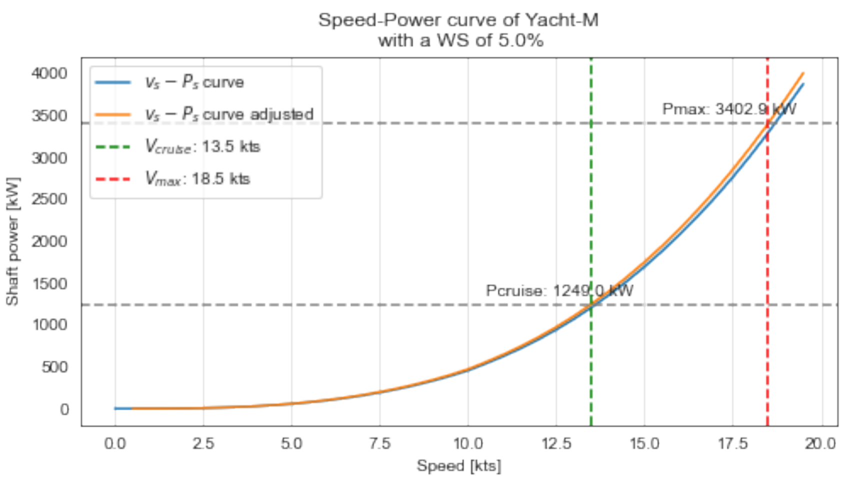


Figure E.12: The adjusted speed power curve for Yacht-M with a weight-share addition of 5.0%.

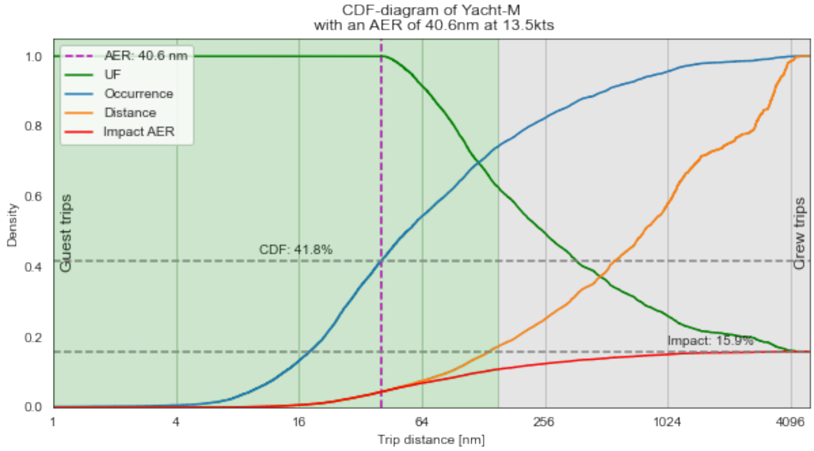


Figure E.13: The CDF of Yacht-M version 1.

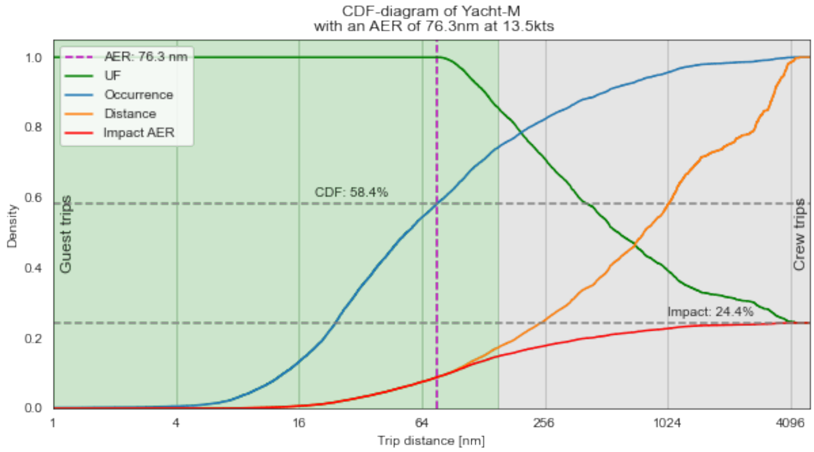


Figure E.14: The CDF of Yacht-M version 2.

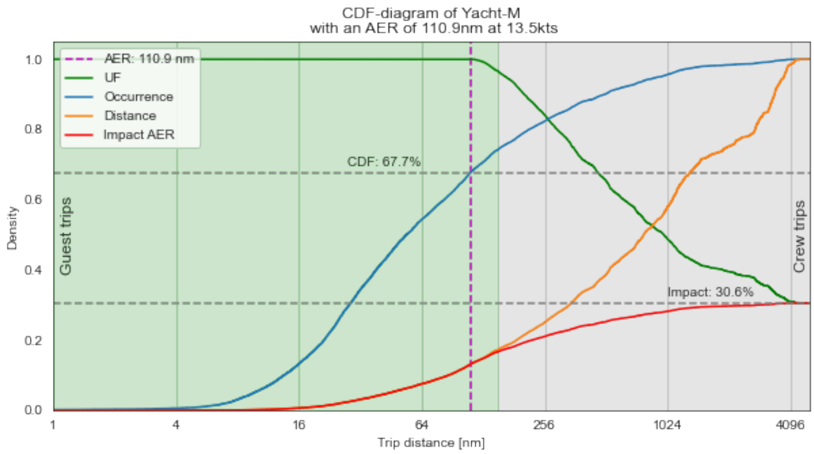


Figure E.15: The CDF of Yacht-M version 3.

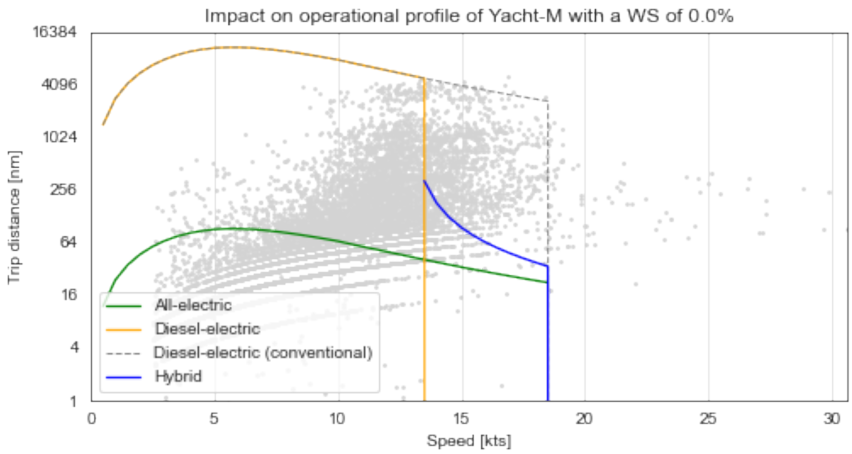


Figure E.16: The impact on the operational profile of Yacht-M with a weight-share addition of 0.0%.

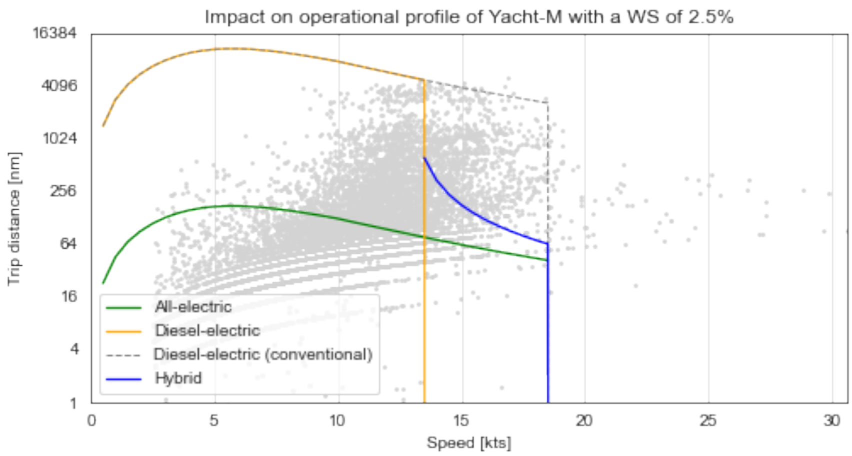


Figure E.17: The impact on the operational profile of Yacht-M with a weight-share addition of 2.5%.

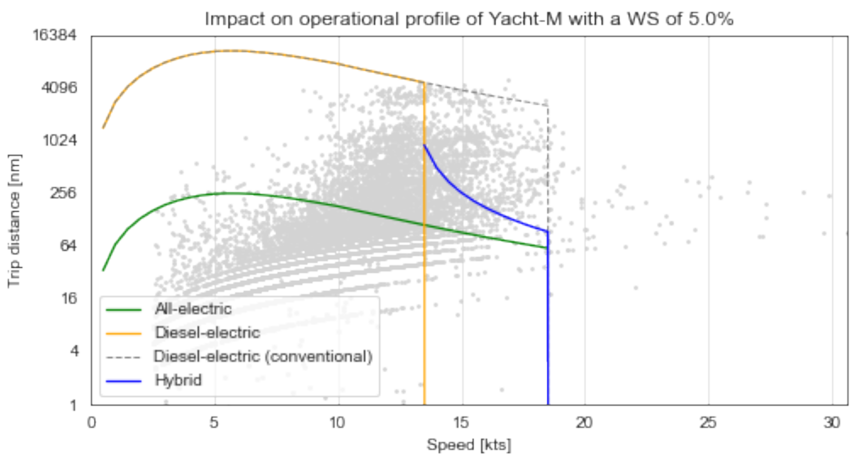


Figure E.18: The impact on the operational profile of Yacht-M with a weight-share addition of 5.0%.

E.3. Yacht-L

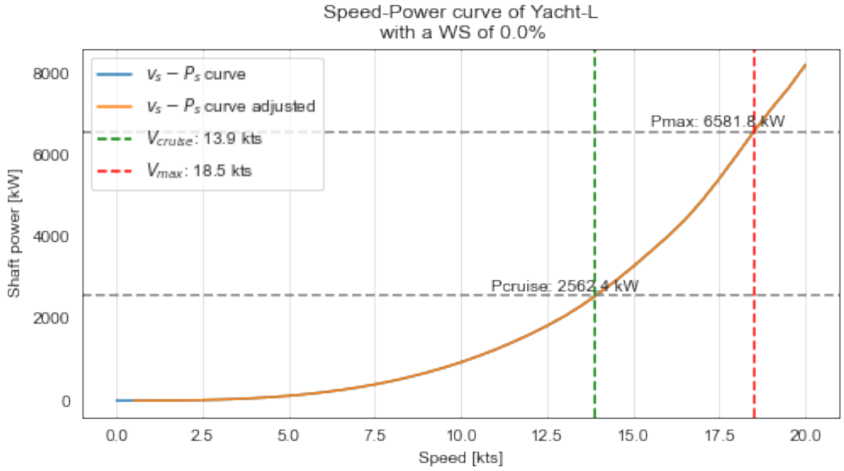


Figure E.19: The adjusted speed power curve for Yacht-L with a weight-share addition of 0.0%.

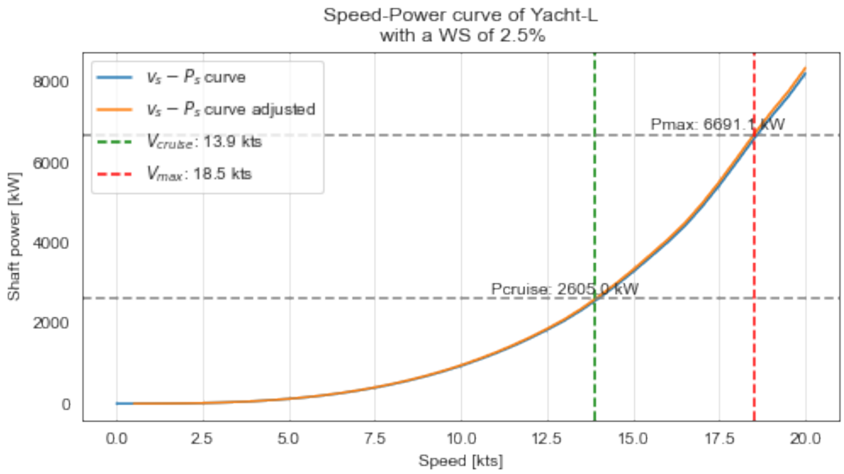


Figure E.20: The adjusted speed power curve for Yacht-L with a weight-share addition of 2.5%.

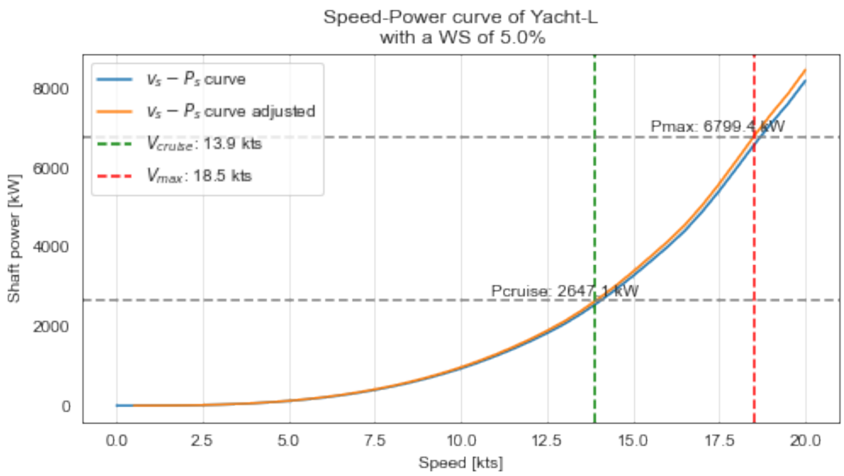


Figure E.21: The adjusted speed power curve for Yacht-L with a weight-share addition of 5.0%.

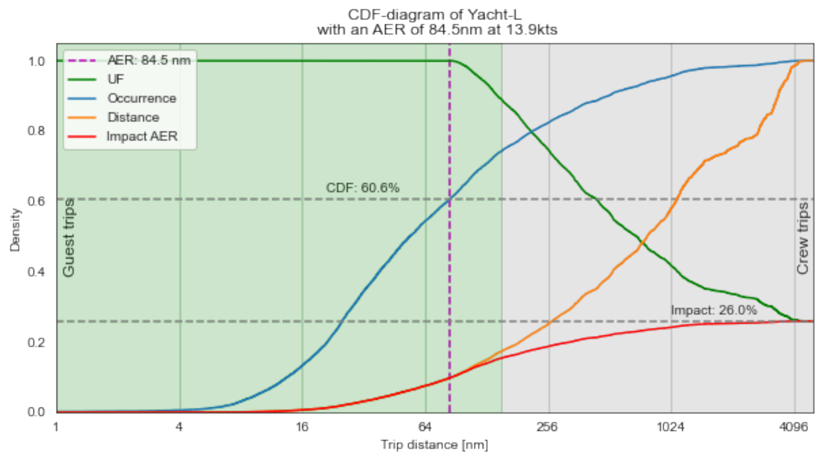


Figure E.22: The CDF of Yacht-L version 1.

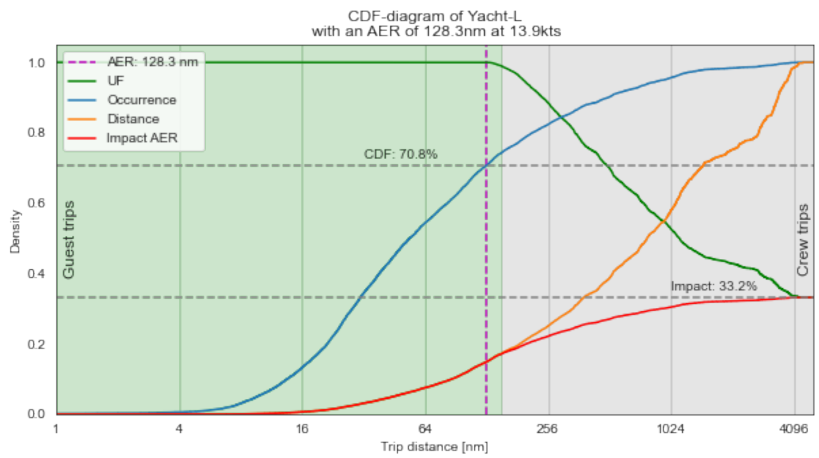


Figure E.23: The CDF of Yacht-L version 2.

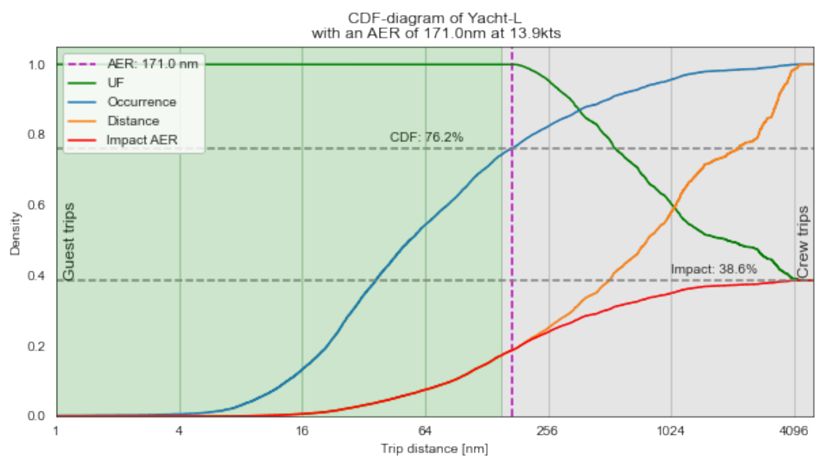


Figure E.24: The CDF of Yacht-L version 3.

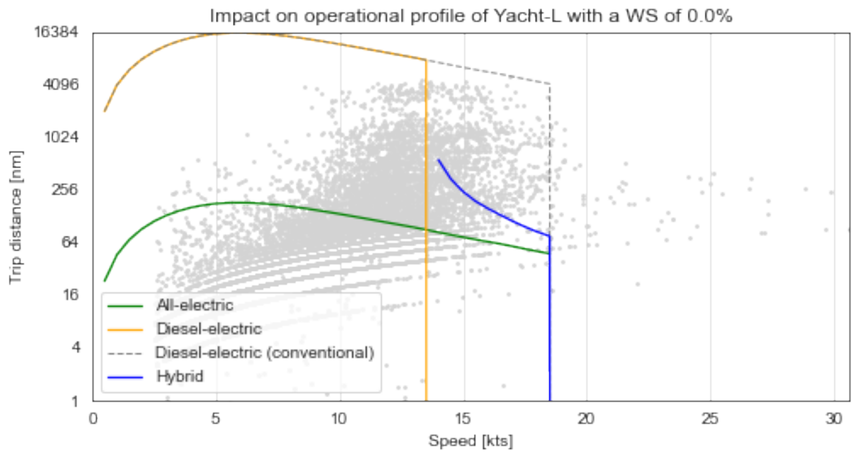


Figure E.25: The impact on the operational profile of Yacht-L with a weight-share addition of 0.0%.

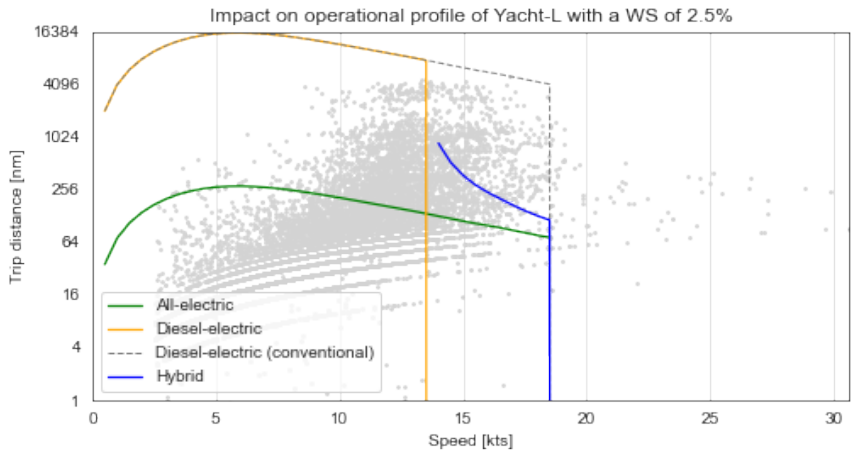


Figure E.26: The impact on the operational profile of Yacht-L with a weight-share addition of 2.5%.

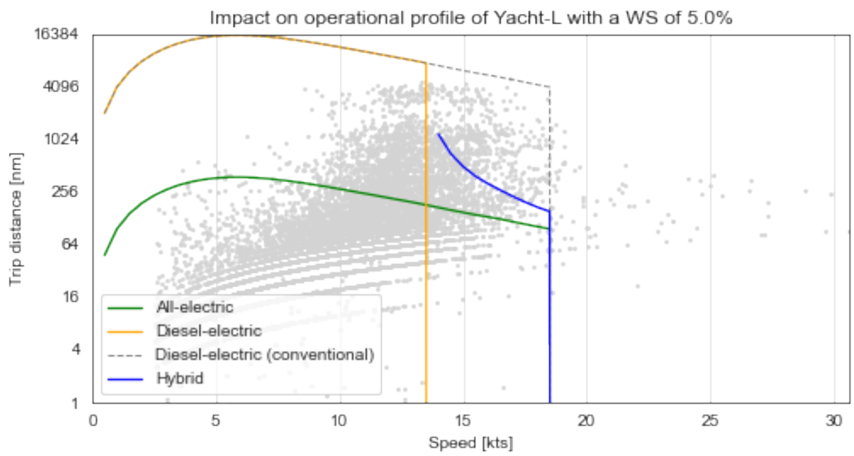


Figure E.27: The impact on the operational profile of Yacht-L with a weight-share addition of 5.0%.

F

Test Itinerary

In this appendix, the different resulting figures of the test itinerary are shown. The figures are grouped per yacht. At the end of this appendix, the elaborate description of the test itinerary is presented.

F.1. Yacht-S

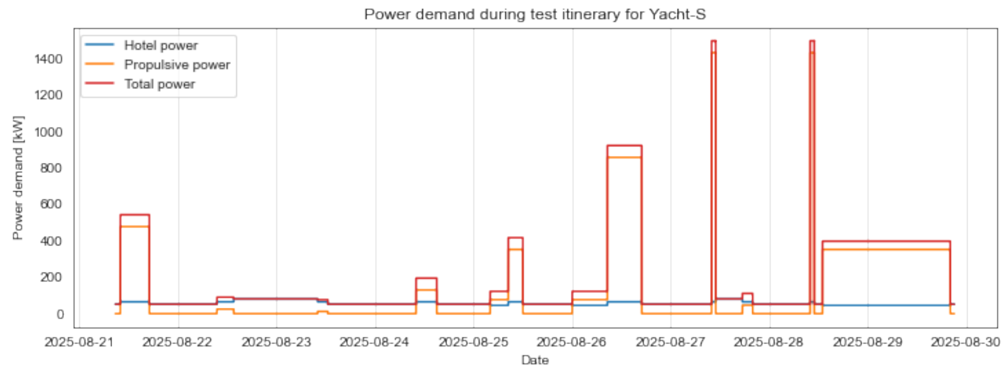


Figure F.1: The power demand of Yacht-S over the course of the test itinerary.

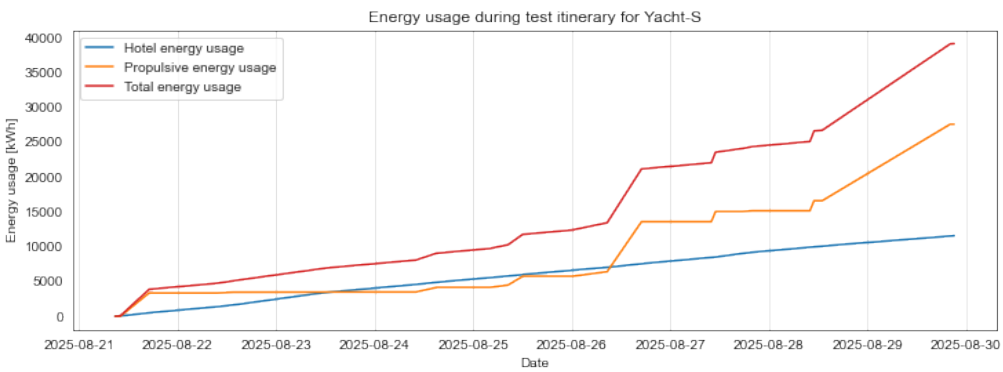


Figure F.2: The energy consumption of Yacht-S over the course of the test itinerary.

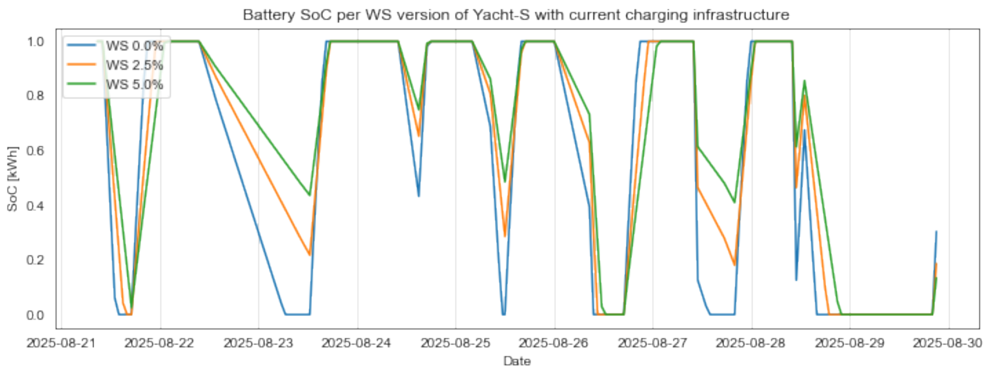


Figure F.3: The State-of-Charge of the installed battery per concept version of Yacht-S with the current available shore power connection of 320kW over the course of the test itinerary.

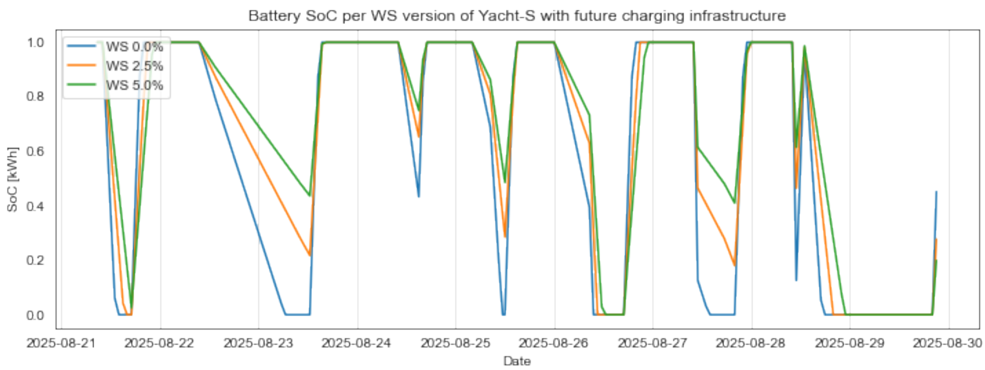


Figure F.4: The State-of-Charge of the installed battery per concept version of Yacht-S with the expected future available shore power connection of 600kW over the course of the test itinerary.

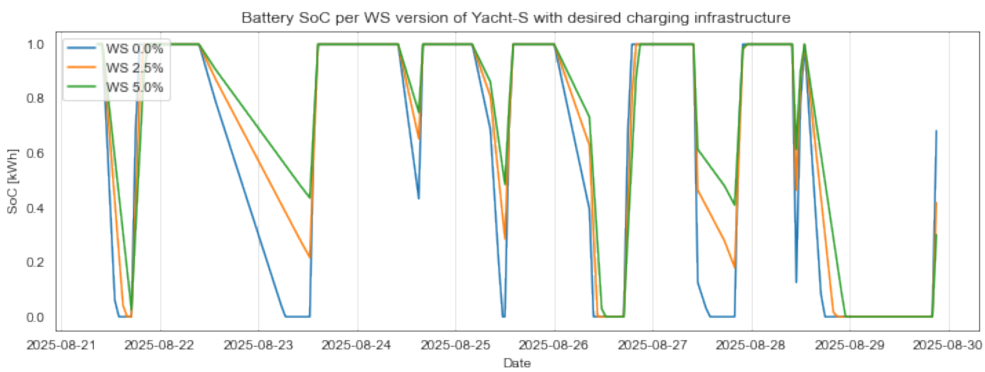


Figure F.5: The State-of-Charge of the installed battery per concept version of Yacht-S with the desired future available shore power connection of 1000kW over the course of the test itinerary.

F.2. Yacht-L

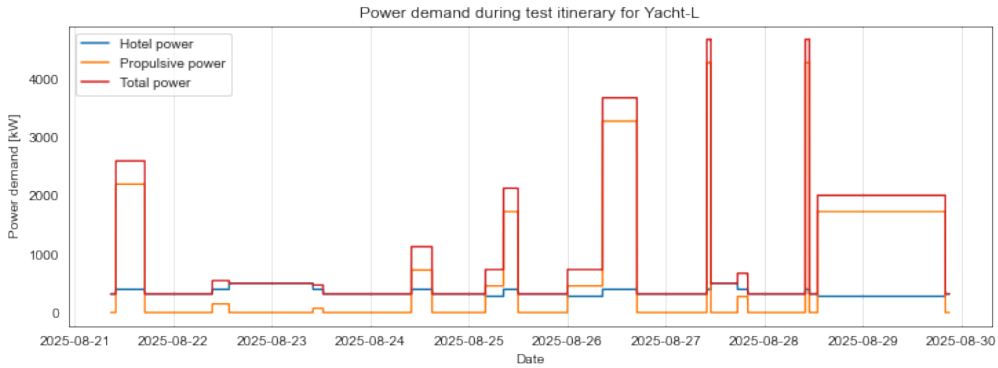


Figure F.6: The power demand of Yacht-L over the course of the test itinerary.

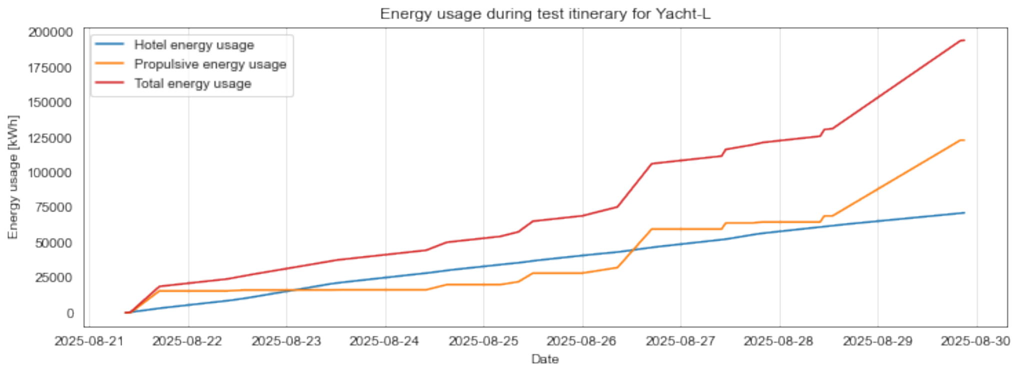


Figure F.7: The energy consumption of Yacht-L over the course of the test itinerary.

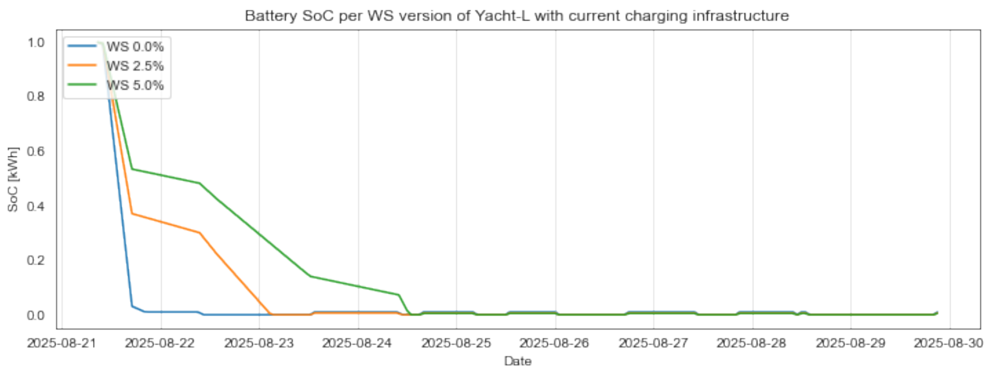


Figure F.8: The State-of-Charge of the installed battery per concept version of Yacht-L with the current available shore power connection of 320kW over the course of the test itinerary.

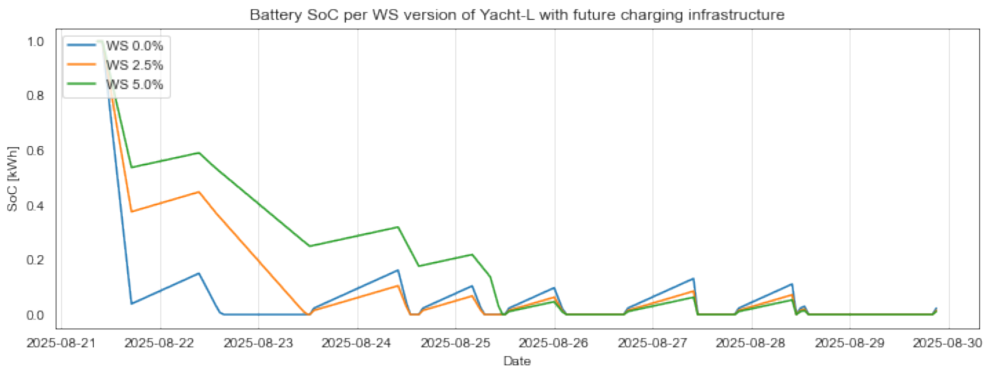


Figure F.9: The State-of-Charge of the installed battery per concept version of Yacht-L with the expected future available shore power connection of 600kW over the course of the test itinerary.

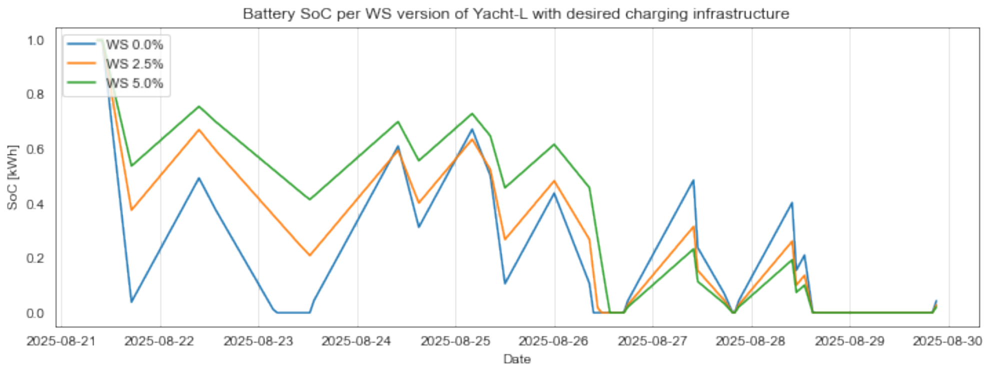
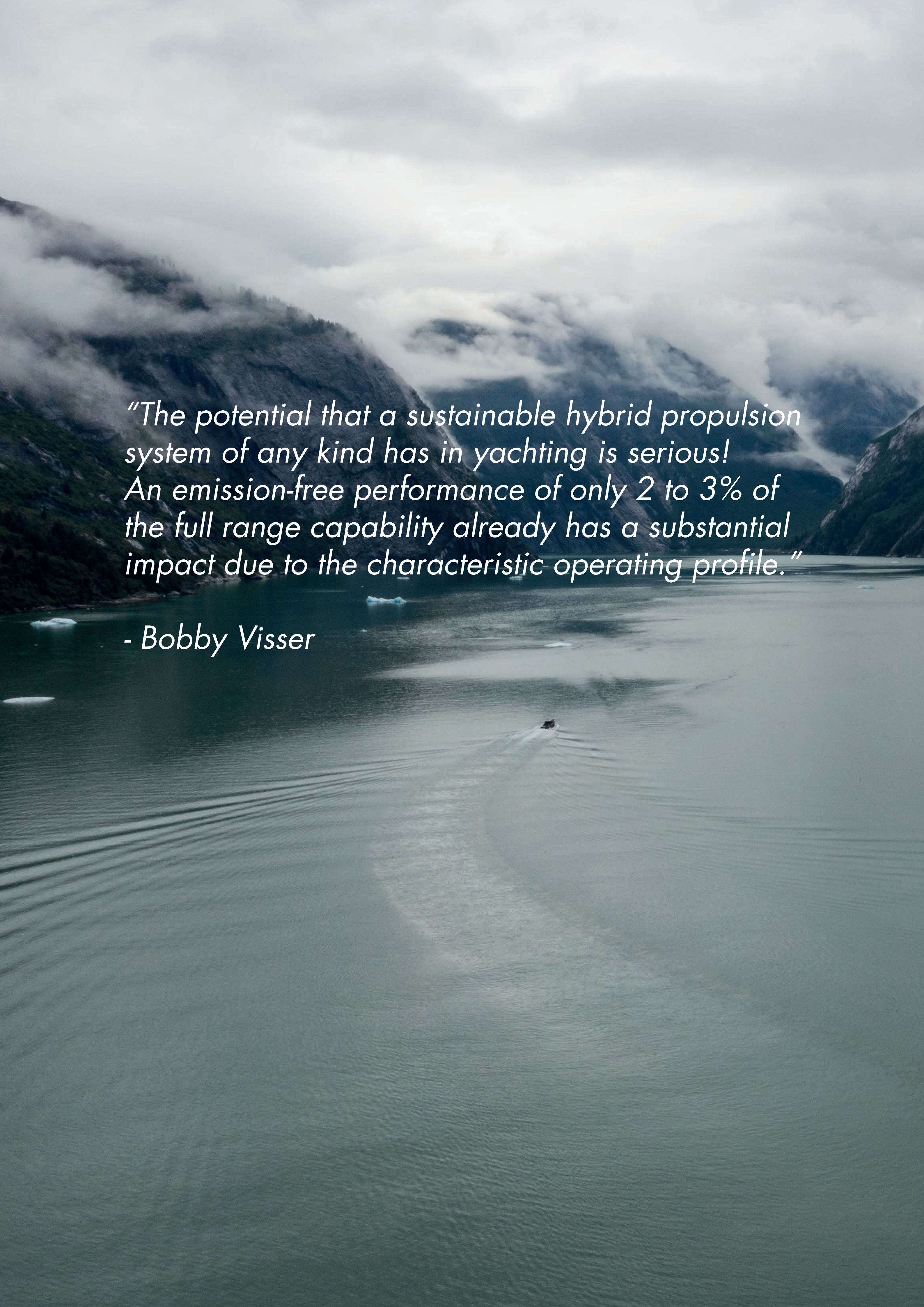


Figure F.10: The State-of-Charge of the installed battery per concept version of Yacht-L with the desired future available shore power connection of 1000kW over the course of the test itinerary.

Table F.1: An elaborate description of the test cruise in the Mediterranean.

Date	Duration [hrs]	Speed [knots]	Distance [nm]	Operation	Location
21/08/25 8:45		0.0	0	In harbour - Guests arrive	Monaco
21/08/25 9:59	1.3	0.0			
21/08/25 10:00		13.0	92	Cruising	Monaco
21/08/25 17:02	7.1	13.0			Calvi (Corsica)
21/08/25 17:03		0.0	0	In harbour	Calvi (Corsica)
22/08/25 9:29	16.5	0.0			
22/08/25 9:30		5.3	22	Cruising	Calvi (Corsica)
22/08/25 13:34	4.1	5.3			Malfacu bay
22/08/25 13:35		0.0	0	At anchor	Malfacu bay
23/08/25 10:00	20.4	0.0			
23/08/25 10:01		4.2	10	Cruising	Malfacu bay
23/08/25 12:28	2.5	4.2			Saint-Florent
23/08/25 12:29		0.0	0	In harbour	Saint-Florent
24/08/25 9:58	21.5	0.0			
24/08/25 9:59		9.0	45	Cruising	Saint-Florent
24/08/25 15:01	5.0	9.0			Bastia
24/08/25 15:02		0.0	0	In harbour	Bastia
25/08/25 4:01	13.0	0.0			
25/08/25 4:02		7.7	34	Early departure for transit	Bastia
25/08/25 8:26	4.4	7.7			Porto Santo Stefano
25/08/25 8:27		12.0	43	Remaining part cruise	Bastia
25/08/25 11:59	3.6	12.0			Porto Santo Stefano
25/08/25 12:00		0.0	0	In harbour	Porto Santo Stefano
25/08/25 23:59	12.0	0.0			
26/08/25 0:00		7.7	66	Early departure for transit	Porto Santo Stefano
26/08/25 8:33	8.6	7.7			Capri
26/08/25 8:34		14.7	123	Remaining part cruise	Porto Santo Stefano
26/08/25 16:55	8.4	14.7			Capri
26/08/25 16:56		0.0	0	In harbour	Capri
27/08/25 9:55	17.0	0.0			
27/08/25 9:56		16.0	16	Cruising	Capri
27/08/25 10:56	1.0	16.0			Napoli
27/08/25 10:57		0.0	0	At anchor	Napoli
27/08/25 17:26	6.5	0.0			
27/08/25 17:27		6.5	16	Cruising	Napoli
27/08/25 19:56	2.5	6.5			Capri
27/08/25 19:57		0.0	0	In harbour	Capri
28/08/25 9:56	14.0	0.0			
28/08/25 9:57		16.0	16	Cruising	Capri
28/08/25 10:56	1.0	16.0			Napoli
28/08/25 10:57		0.0	0	In harbour - Guests departure	Napoli
28/08/25 12:56	2.0	0.0			
28/08/25 12:57		12.0	374	Crew only transit	Napoli
29/08/25 20:05	31.1	12.0			Monaco
29/08/25 20:06		0.0	0	Arrived in main marina	Monaco
29/08/25 21:06	1.0	0.0			



"The potential that a sustainable hybrid propulsion system of any kind has in yachting is serious! An emission-free performance of only 2 to 3% of the full range capability already has a substantial impact due to the characteristic operating profile."

- Bobby Visser